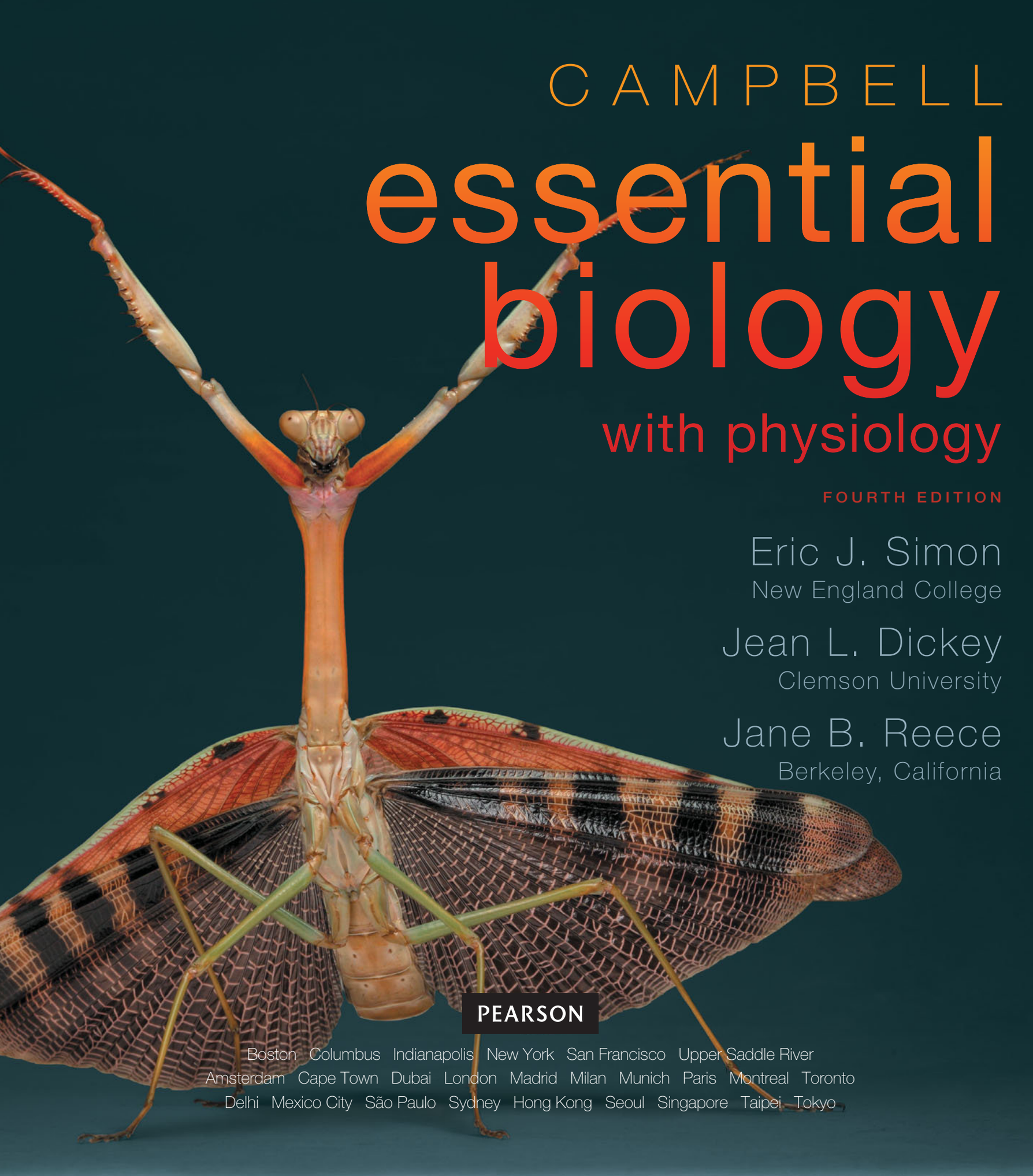


CAMPBELL

essential biology

with physiology

FOURTH EDITION

Eric J. Simon
New England College

Jean L. Dickey
Clemson University

Jane B. Reece
Berkeley, California

PEARSON

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto
Delhi Mexico City São Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Editorial Director: *Michael Young*
Editor-in-Chief: *Beth Wilbur*
Executive Director of Development: *Deborah Gale*
Executive Editor: *Chalon Bridges*
Senior Editorial Manager: *Ginnie Simione Jutson*
Development Editors: *Evelyn Dahlgren, Debbie Hardin, Kim Krummel*
Senior Supplements Project Editor: *Susan Berge*
Associate Editor: *Logan Triglia*
Editorial Assistant: *Rachel Brickner*
Director of Production: *Erin Gregg*
Managing Editor: *Michael Early*
Assistant Managing Editor: *Shannon Tozier*
Supplements Production Project Manager: *Jane Brundage*
Production Management and Composition: *S4Carlisle Publishing Services*
Illustrations: *Precision Graphics*
Design Manager and Interior Designer: *Marilyn Perry*
Cover Designer: *Riezebos Holzbaur Design Group*
Senior Photo Editor: *Donna Kalal*
Photo Researcher: *Kristin Piljay*
Manager, Rights and Permissions: *Beth Wollar*
Manufacturing Buyer: *Michael Penne*
Director of Media Development: *Lauren Fogel*
Senior Media Producer: *Jonathan Ballard*
Associate Media Project Manager (IRDVD): *Shannon Kong*
Associate Web Developer: *Pete Ratkevich*
Director of Editorial Content, MasteringBiology®: *Natania Mlawer*
Development Editor, MasteringBiology®: *Sarah Jensen*
Project Editor, Mastering Biology®: *Juliana Tringali*
Senior Mastering Media Producer: *Katie Foley*
Director of Marketing: *Christy Lesko*
Executive Marketing Manager: *Lauren Harp*
Executive Marketing Manager, Mastering: *Scott Dustan*
Marketing Manager: *Lauren Rodgers*
Text Printer: *Courier Kendallville*
Cover Printer: *Lehigh-Phoenix Color/Hagerstown*

Cover Photo Credit: Igor Siwanowicz/Fame Pictures, Inc.; African Mega Mantis, *Plistospilota guineensis* male

Credits and acknowledgments borrowed from other sources and reproduced, with permission, in this textbook appear on page A-5.

Copyright © 2013, 2010, 2007 Pearson Education, Inc. All rights reserved. Manufactured in the United States of America. This publication is protected by Copyright, and permission should be obtained from the publisher prior to any prohibited reproduction, storage in a retrieval system, or transmission in any form or by any means, electronic, mechanical, photocopying, recording, or likewise. To obtain permission(s) to use material from this work, please submit a written request to Pearson Education, Inc., Permissions Department, 1900 E. Lake Ave., Glenview, IL 60025. For information regarding permissions, call (847) 486-2635.

Many of the designations used by manufacturers and sellers to distinguish their products are claimed as trademarks. Where those designations appear in this book, and the publisher was aware of a trademark claim, the designations have been printed in initial caps or all caps.

MasteringBiology™ is a trademark, in the U.S. and/or other countries, of Pearson Education, Inc., or its affiliates.

Library of Congress Cataloging-in-Publication Data
Simon, Eric J. (Eric Jeffrey), 1967-
Campbell essential biology with physiology / Eric J. Simon, Jane B. Reece, Jean L. Dickey.--4th ed.
p. cm.
Includes index.
ISBN-13: 978-0-321-77260-2
ISBN-10: 0-321-77260-1
1. Biology--Textbooks. 2. Physiology--Textbooks. 3. Plant physiology--Textbooks. I. Reece, Jane B. II. Dickey, Jean. III. Title.
QH308.2.C344 2013
570--dc23

2011038831

1 2 3 4 5 6 7 8 9 10—CRK—16 15 14 13 12

ISBN 10: 0-321-77260-1; ISBN 13: 978-0-321-77260-2 (Student edition)
ISBN 10: 0-321-78825-7; ISBN 13: 978-0-321-78825-2 (Books à la Carte edition)

PEARSON

www.pearsonhighered.com

Dorling Kindersley Limited,
80 Strand,
London WC2R ORL.

About the Authors



ERIC J. SIMON

is an associate professor in the Department of Biology and Health Science at New England College, in Henniker, New Hampshire. He teaches introductory biology to science majors and nonscience majors, as well as upper-level courses in genetics, microbiology, tropical marine biology, and careers in science. Dr. Simon received a B.A. in biology and computer science and an M.A. in biology from Wesleyan University and a Ph.D. in biochemistry from Harvard University. His research focuses on innovative ways to use technology to improve teaching and learning in the science classroom, particularly for nonscience majors. Dr. Simon is also a coauthor of *Campbell Biology: Concepts & Connections*, 7th Edition.

To Marshall, an intellectual role model, a source of data and wisdom, an organizational tour de force, a hardcore bicyclist, a bona fide Deadhead, a great father, and one cool dude



JEAN L. DICKEY

is a professor of biology at Clemson University in South Carolina. She had no idea that science was interesting until her senior year in high school, when a scheduling problem landed her in an advanced biology course. Abandoning plans to study English or foreign languages, she enrolled in Kent State University as a biology major. After receiving her B.S. in biology, she went on to earn a Ph.D. in ecology and evolution from Purdue University. Since joining the faculty at Clemson in 1984, Dr. Dickey has specialized in teaching nonscience majors, including a course designed for pre-service elementary teachers and workshops for in-service teachers. She also developed an investigative laboratory curriculum for general biology. Dr. Dickey is the author of *Laboratory Investigations for Biology*, 2nd Edition, and is a coauthor of *Campbell Biology: Concepts & Connections*, 7th Edition.

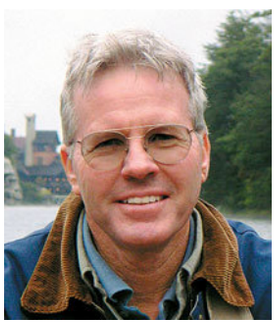
To my mother, who taught me to love learning, and to my daughters Katherine and Jessie, the twin delights of my life



JANE B. REECE

has worked in biology publishing since 1978, when she joined the editorial staff of Benjamin Cummings. Her education includes an A.B. in biology from Harvard University (where she was initially a philosophy major), an M.S. in microbiology from Rutgers University, and a Ph.D. in bacteriology from the University of California, Berkeley. At UC Berkeley, and later as a postdoctoral fellow in genetics at Stanford University, her research focused on genetic recombination in bacteria. Dr. Reece taught biology at Middlesex County College (New Jersey) and Queensborough Community College (New York). During her 12 years as an editor at Benjamin Cummings, she played a major role in a number of successful textbooks. She is the lead author of *Campbell Biology*, 9th Edition, and *Campbell Biology: Concepts & Connections*, 7th Edition.

To my wonderful coauthors, who have made working on our books a pleasure



NEIL A. CAMPBELL

(1946–2004) combined the inquiring nature of a research scientist with the soul of a caring teacher. Over his 30 years of teaching introductory biology to both science majors and nonscience majors, many thousands of students had the opportunity to learn from him and be stimulated by his enthusiasm for the study of life. While he is greatly missed by his many friends in the biology community, his coauthors remain inspired by his visionary dedication to education and are committed to searching for ever-better ways to engage students in the wonders of biology.

Detailed Contents

1 Introduction: Biology Today 2

CHAPTER THREAD: BIOLOGY IN OUR EVERYDAY LIVES

BIOLOGY AND SOCIETY
Biology All Around Us 3

The Scope of Life **4**
The Properties of Life 4
Life at Its Many Levels 4
Life in Its Diverse Forms 8

Evolution: Biology's Unifying Theme **10**
The Darwinian View of Life 10
Natural Selection 11

The Process of Science **14**
Discovery Science 14
Hypothesis-Driven Science 14

THE PROCESS OF SCIENCE
Are Trans Fats Bad for You? 15
Theories in Science 16
The Culture of Science 17
Science, Technology, and Society 17

EVOLUTION CONNECTION
Evolution in Our Everyday Lives 18





UNIT 1: Cells

2 Essential Chemistry for Biology 22

CHAPTER THREAD: LIFE'S DEPENDENCE ON WATER

BIOLOGY AND SOCIETY
More Precious than Gold 23

Some Basic Chemistry **24**
Matter: Elements and Compounds 24
Atoms 25
Chemical Bonding and Molecules 27
Chemical Reactions 28

Water and Life **29**
Water's Life-Supporting Properties 29

THE PROCESS OF SCIENCE
Can Exercise Boost Your Brain Power? 31
Acids, Bases, and pH 32

EVOLUTION CONNECTION
The Search for Extraterrestrial Life 33

3 The Molecules of Life 36

CHAPTER THREAD: LACTOSE INTOLERANCE

BIOLOGY AND SOCIETY
Got Lactose? 37

Organic Compounds **38**
Carbon Chemistry 38
Giant Molecules from Smaller Building Blocks 39

Large Biological Molecules **40**
Carbohydrates 40
Lipids 43
Proteins 46
Nucleic Acids 49

THE PROCESS OF SCIENCE
Does Lactose Intolerance Have a Genetic Basis? 51

EVOLUTION CONNECTION
The Evolution of Lactose Intolerance in Humans 51

4 A Tour of the Cell 54

CHAPTER THREAD: ANTIBIOTIC-RESISTANT BACTERIA

BIOLOGY AND SOCIETY
Antibiotics: Drugs that Target Bacterial Cells 55

The Microscopic World of Cells **56**
Microscopes as Windows on the World of Cells 56
The Two Major Categories of Cells 58
An Overview of Eukaryotic Cells 59

Membrane Structure **60**
The Plasma Membrane: A Fluid Mosaic of Lipids and Proteins 60

THE PROCESS OF SCIENCE
What Makes a Superbug? 61
Cell Surfaces 61

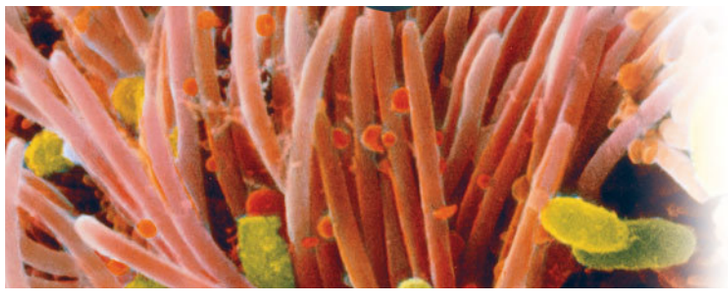
The Nucleus and Ribosomes: Genetic Control of the Cell **62**
Structure and Function of the Nucleus 62
Ribosomes 63
How DNA Directs Protein Production 63

The Endomembrane System: Manufacturing and Distributing Cellular Products **64**
The Endoplasmic Reticulum 64
The Golgi Apparatus 65
Lysosomes 66
Vacuoles 67

Chloroplasts and Mitochondria: Energy Conversion **68**
Chloroplasts 68
Mitochondria 68

The Cytoskeleton: Cell Shape and Movement **69**
Maintaining Cell Shape 69
Cilia and Flagella 70

EVOLUTION CONNECTION
The Evolution of Antibiotic Resistance 71



5 The Working Cell 74

CHAPTER THREAD: NANOTECHNOLOGY

BIOLOGY AND SOCIETY
Harnessing Cellular Structures 75

Some Basic Energy Concepts **76**
Conservation of Energy 76
Entropy 77
Chemical Energy 77
Food Calories 78

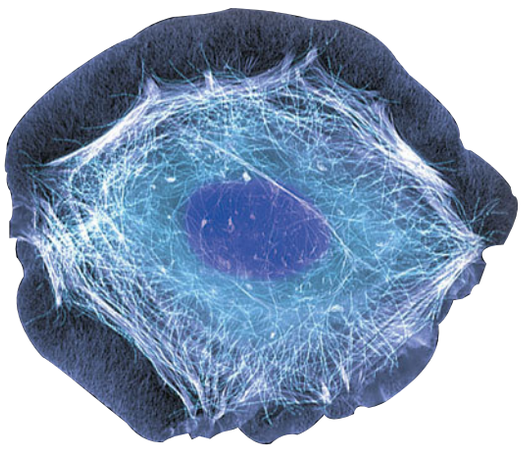
ATP and Cellular Work **79**
The Structure of ATP 79
Phosphate Transfer 79
The ATP Cycle 80

Enzymes **80**
Activation Energy 80

THE PROCESS OF SCIENCE
Can Enzymes Be Engineered? 81
Induced Fit 82
Enzyme Inhibitors 82

Membrane Function **83**
Passive Transport: Diffusion across Membranes 83
Osmosis and Water Balance 84
Active Transport: The Pumping of Molecules across Membranes 86
Exocytosis and Endocytosis: Traffic of Large Molecules 86
The Role of Membranes in Cell Signaling 87

EVOLUTION CONNECTION
The Origin of Membranes 87



6 Cellular Respiration: Obtaining Energy from Food 90

CHAPTER THREAD: AEROBIC VERSUS ANAEROBIC LIFESTYLES

BIOLOGY AND SOCIETY
Marathoners versus Sprinters 91

Energy Flow and Chemical Cycling in the Biosphere **92**
Producers and Consumers 92
Chemical Cycling between Photosynthesis and Cellular Respiration 92

Cellular Respiration: Aerobic Harvest of Food Energy **94**
The Simplified Equation for Cellular Respiration 94
The Role of Oxygen in Cellular Respiration 95
An Overview of Cellular Respiration 96
The Three Stages of Cellular Respiration 97
The Results of Cellular Respiration 100

Fermentation: Anaerobic Harvest of Food Energy **101**
Fermentation in Human Muscle Cells 101

THE PROCESS OF SCIENCE
What Causes Muscle Burn? 102
Fermentation in Microorganisms 102

EVOLUTION CONNECTION
Life before and after Oxygen 103



7 Photosynthesis: Using Light to Make Food 106

CHAPTER THREAD: GREEN ENERGY

BIOLOGY AND SOCIETY
Biofuels 107

The Basics of Photosynthesis **108**
Chloroplasts: Sites of Photosynthesis 108
The Simplified Equation for Photosynthesis 109
A Photosynthesis Road Map 110

The Light Reactions: Converting Solar Energy to Chemical Energy **110**
The Nature of Sunlight 110

THE PROCESS OF SCIENCE
What Colors of Light Drive Photosynthesis? 111
Chloroplast Pigments 112
How Photosystems Harvest Light Energy 112
How the Light Reactions Generate ATP and NADPH 113

The Calvin Cycle: Making Sugar from Carbon Dioxide **115**

EVOLUTION CONNECTION
Solar-Driven Evolution 115



UNIT 2: Genetics

8 Cellular Reproduction: Cells from Cells 120

CHAPTER THREAD: LIFE WITH AND WITHOUT SEX

BIOLOGY AND SOCIETY
Virgin Birth of a Dragon 121

What Cell Reproduction Accomplishes **122**

The Cell Cycle and Mitosis **123**
Eukaryotic Chromosomes 123
The Cell Cycle 125
Mitosis and Cytokinesis 126
Cancer Cells: Growing Out of Control 128

Meiosis, the Basis of Sexual Reproduction **130**
Homologous Chromosomes 130
Gametes and the Life Cycle of a Sexual Organism 131
The Process of Meiosis 132
Review: Comparing Mitosis and Meiosis 134
The Origins of Genetic Variation 135

THE PROCESS OF SCIENCE
Do All Animals Have Sex? 137
When Meiosis Goes Awry 138

EVOLUTION CONNECTION
The Advantages of Sex 140



9 Patterns of Inheritance 144

CHAPTER THREAD: DOG BREEDING

BIOLOGY AND SOCIETY
Our Longest-Running Genetic Experiment: Dogs 145

Heritable Variation and Patterns of Inheritance 146
In an Abbey Garden 146
Mendel's Law of Segregation 147
Mendel's Law of Independent Assortment 150
Using a Testcross to Determine an Unknown Genotype 152
The Rules of Probability 152
Family Pedigrees 153
Human Disorders Controlled by a Single Gene 154

THE PROCESS OF SCIENCE
What Is the Genetic Basis of Coat Variation in Dogs? 157

Variations on Mendel's Laws 158
Incomplete Dominance in Plants and People 158
ABO Blood Groups: An Example of Multiple Alleles and Codominance 159
Pleiotropy and Sickle-Cell Disease 160
Polygenic Inheritance 160
The Role of Environment 161

The Chromosomal Basis of Inheritance 162
Linked Genes 163
Genetic Recombination: Crossing Over 163
Linkage Maps 164

Sex Chromosomes and Sex-Linked Genes 165
Sex Determination in Humans 165
Sex-Linked Genes 165

EVOLUTION CONNECTION
Barking Up the Evolutionary Tree 167



10 The Structure and Function of DNA 172

CHAPTER THREAD: THE DEADLIEST VIRUS

BIOLOGY AND SOCIETY
Mix-and-Match Viruses 173

DNA: Structure and Replication 174
DNA and RNA Structure 174
Watson and Crick's Discovery of the Double Helix 175
DNA Replication 177

The Flow of Genetic Information from DNA to RNA to Protein 178
How an Organism's Genotype Determines Its Phenotype 178
From Nucleotides to Amino Acids: An Overview 179
The Genetic Code 180
Transcription: From DNA to RNA 181
The Processing of Eukaryotic RNA 182
Translation: The Players 182
Translation: The Process 184
Review: DNA → RNA → Protein 185
Mutations 186

Viruses and Other Noncellular Infectious Agents 188
Bacteriophages 188
Plant Viruses 190
Animal Viruses 190

THE PROCESS OF SCIENCE
Do Flu Vaccines Protect the Elderly? 192
HIV, the AIDS Virus 192
Viroids and Prions 194

EVOLUTION CONNECTION
Emerging Viruses 194



11 How Genes Are Controlled 198

CHAPTER THREAD: CANCER

BIOLOGY AND SOCIETY
Tobacco's Smoking Gun 199

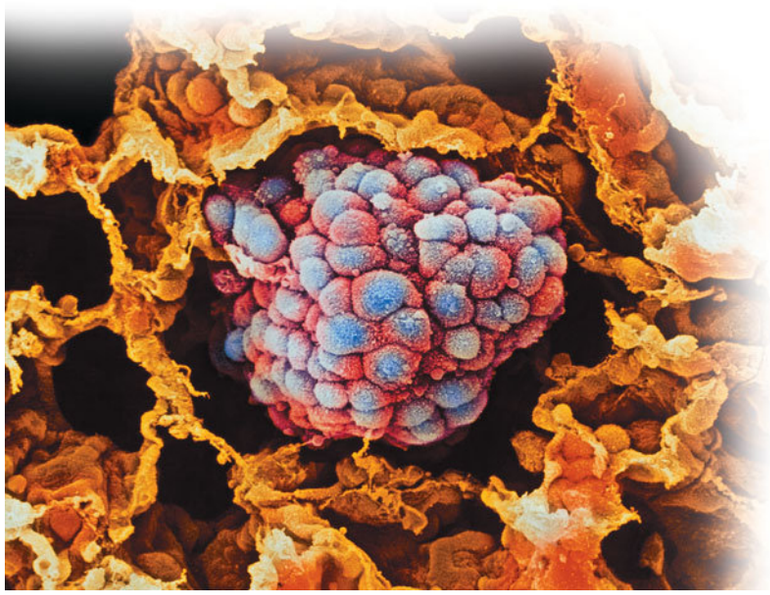
How and Why Genes Are Regulated **200**
Patterns of Gene Expression in Differentiated Cells 200
Gene Regulation in Bacteria 200
Gene Regulation in Eukaryotic Cells 202
Cell Signaling 205
Homeotic Genes 205
DNA Microarrays: Visualizing Gene Expression 206

Cloning Plants and Animals **207**
The Genetic Potential of Cells 207
Reproductive Cloning of Animals 208
Therapeutic Cloning and Stem Cells 210

The Genetic Basis of Cancer **211**
Genes That Cause Cancer 211

THE PROCESS OF SCIENCE
Are Childhood Tumors Special? 212
Cancer Risk and Prevention 214

EVOLUTION CONNECTION
The Evolution of Cancer in the Body 215



12 DNA Technology 218

CHAPTER THREAD: DNA PROFILING

BIOLOGY AND SOCIETY
DNA, Guilt, and Innocence 219

Recombinant DNA Technology **220**
Applications: From Humulin to Foods to "Pharm" Animals 220
Recombinant DNA Techniques 222

DNA Profiling and Forensic Science **226**
Investigating Murder, Paternity, and Ancient DNA 226
DNA Profiling Techniques 227

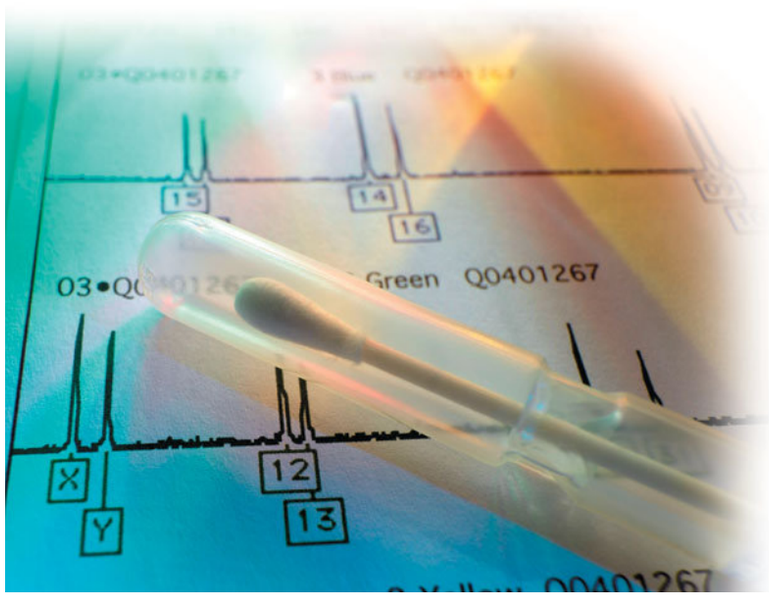
Genomics and Proteomics **230**
The Human Genome Project 230
Tracking the Anthrax Killer 231
Genome-Mapping Techniques 232

THE PROCESS OF SCIENCE
Can Genomics Cure Cancer? 233
Proteomics 233

Human Gene Therapy **234**

Safety and Ethical Issues **235**
The Controversy over Genetically Modified Foods 235
Ethical Questions Raised by DNA Technology 236

EVOLUTION CONNECTION
The Y Chromosome as a Window on History 237



UNIT 3: Evolution and Diversity

13 How Populations Evolve 242

CHAPTER THREAD: EVOLUTION IN ACTION

BIOLOGY AND SOCIETY
Mosquitoes, Microbes, and Malaria 243

Charles Darwin and *The Origin of Species* 244
Darwin's Cultural and Scientific Context 245
Descent with Modification 247

Evidence of Evolution 248
The Fossil Record 248
Biogeography 249
Comparative Anatomy 250
Comparative Embryology 251
Molecular Biology 251

Natural Selection 252
Darwin's Theory of Natural Selection 252
Natural Selection in Action 253

THE PROCESS OF SCIENCE
Does Predation Drive the Evolution of Lizard Horn Length? 254
Evolutionary Trees 255

The Modern Synthesis: Darwinism Meets Genetics 256
Populations as the Units of Evolution 256
Genetic Variation in Populations 257
Analyzing Gene Pools 258
Population Genetics and Health Science 259
Microevolution as Change in a Gene Pool 259

Mechanisms of Evolution 260
Genetic Drift 260
Gene Flow 262
Natural Selection: A Closer Look 262
Sexual Selection 264

EVOLUTION CONNECTION
An Evolutionary Response to Malaria 265

14 How Biological Diversity Evolves 268

CHAPTER THREAD: MASS EXTINCTIONS

BIOLOGY AND SOCIETY
The Sixth Mass Extinction 269

The Origin of Species 270
What Is a Species? 271
Reproductive Barriers between Species 272
Mechanisms of Speciation 274
What Is the Pace of Speciation? 277

The Evolution of Biological Novelty 278
Adaptation of Old Structures for New Functions 278
Evo-Devo: Development and Evolutionary Novelty 279

Earth History and Macroevolution 280
Geologic Time and the Fossil Record 280
Plate Tectonics and Macroevolution 283
Mass Extinctions and Explosive Diversifications of Life 284

THE PROCESS OF SCIENCE
Did a Meteor Kill the Dinosaurs? 284

Classifying the Diversity of Life 285
Some Basics of Taxonomy 285
Classification and Phylogeny 286
Classification: A Work in Progress 288

EVOLUTION CONNECTION
Rise of the Mammals 289

15 The Evolution of Microbial Life 292

CHAPTER THREAD: HOW LIFE BEGAN

BIOLOGY AND SOCIETY
Has Life Been Created in the Lab? 293

Major Episodes in the History of Life 294

The Origin of Life 296
Resolving the Biogenesis Paradox 296
A Four-Stage Hypothesis for the Origin of Life 296

THE PROCESS OF SCIENCE
Can Biological Monomers Form Spontaneously? 297
From Chemical Evolution to Darwinian Evolution 298

Prokaryotes **299**
They're Everywhere! 299
The Structure and Function of Prokaryotes 300
The Two Main Branches of Prokaryotic Evolution: Bacteria and Archaea 302
Bacteria and Disease 303
The Ecological Impact of Prokaryotes 305

Protists **306**
The Origin of Eukaryotic Cells 306
The Diversity of Protists 307

EVOLUTION CONNECTION
The Origin of Multicellular Life 311

16 Plants, Fungi, and the Move onto Land 314
CHAPTER THREAD: PLANT-FUNGUS SYMBIOSIS

BIOLOGY AND SOCIETY
The Diamond of the Kitchen 315

Colonizing Land **316**
Terrestrial Adaptations of Plants 316
The Origin of Plants from Green Algae 318

Plant Diversity **318**
Highlights of Plant Evolution 318
Bryophytes 319
Ferns 321
Gymnosperms 322
Angiosperms 324
Plant Diversity as a Nonrenewable Resource 327

Fungi **328**
Characteristics of Fungi 329
The Ecological Impact of Fungi 330

THE PROCESS OF SCIENCE
Did a Fungus Lead to the Salem Witch Hunt? 331

EVOLUTION CONNECTION
Mutually Beneficial Symbiosis 332

17 The Evolution of Animals 336
CHAPTER THREAD: HUMAN EVOLUTION

BIOLOGY AND SOCIETY
The Discovery of the Hobbit People 337

The Origins of Animal Diversity **338**
What Is an Animal? 338
Early Animals and the Cambrian Explosion 339
Animal Phylogeny 340

Major Invertebrate Phyla **341**
Sponges 341
Cnidarians 342
Molluscs 343
Flatworms 344
Annelids 345
Roundworms 346
Arthropods 347
Echinoderms 353

Vertebrate Evolution and Diversity **354**
Characteristics of Chordates 354
Fishes 356
Amphibians 357
Reptiles 358
Mammals 360

The Human Ancestry **361**
The Evolution of Primates 361
The Emergence of Humankind 363

THE PROCESS OF SCIENCE
Who Were the Hobbit People? 365

EVOLUTION CONNECTION
Are We Still Evolving? 367



UNIT 4: Ecology

18 An Introduction to Ecology and the Biosphere 372

CHAPTER THREAD: GLOBAL CLIMATE CHANGE

BIOLOGY AND SOCIETY
Penguins and Polar Bears in Peril 373

An Overview of Ecology **374**
Ecology and Environmentalism 374
A Hierarchy of Interactions 375

Living in Earth's Diverse Environments **376**
Abiotic Factors of the Biosphere 376
The Evolutionary Adaptations of Organisms 378
Adjusting to Environmental Variability 378

Biomes **380**
Freshwater Biomes 380
Marine Biomes 382
How Climate Affects Terrestrial Biome Distribution 384
Terrestrial Biomes 385
The Water Cycle 391
Human Impact on Biomes 392

Global Climate Change **394**
The Greenhouse Effect and Global Warming 394
The Accumulation of Greenhouse Gases 395

THE PROCESS OF SCIENCE
How Does Climate Change Affect Species Distribution? 396
Effects of Climate Change on Ecosystems 397
Looking to Our Future 398

EVOLUTION CONNECTION
Climate Change as an Agent of Natural Selection 399



19 Population Ecology 402

CHAPTER THREAD: BIOLOGICAL INVASIONS

BIOLOGY AND SOCIETY
Invasion of the Lionfish 403

An Overview of Population Ecology **404**
Population Density 405
Population Age Structure 405
Life Tables and Survivorship Curves 406
Life History Traits as Evolutionary Adaptations 406

Population Growth Models **408**
The Exponential Population Growth Model: The Ideal of an Unlimited Environment 408
The Logistic Population Growth Model: The Reality of a Limited Environment 409
Regulation of Population Growth 410

Applications of Population Ecology **412**
Conservation of Endangered Species 412
Sustainable Resource Management 412
Invasive Species 413
Biological Control of Pests 414

THE PROCESS OF SCIENCE
Can Biological Control Defeat Kudzu? 415
Integrated Pest Management 416

Human Population Growth **417**
The History of Human Population Growth 417
Age Structures 418
Our Ecological Footprint 419

EVOLUTION CONNECTION
Humans as an Invasive Species 421



20 Communities and Ecosystems 424

CHAPTER THREAD: BIODIVERSITY IN DECLINE

BIOLOGY AND SOCIETY
Why Biodiversity Matters 425

The Loss of Biodiversity **426**
Genetic Diversity 426
Species Diversity 426
Ecosystem Diversity 427
Causes of Declining Biodiversity 427

Community Ecology **428**
Interspecific Interactions 428
Trophic Structure 432
Species Diversity in Communities 435
Disturbances in Communities 436
Ecological Succession 436

Ecosystem Ecology **437**
Energy Flow in Ecosystems 438
Chemical Cycling in Ecosystems 440

Conservation and Restoration Biology **444**
Biodiversity "Hot Spots" 444
Conservation at the Ecosystem Level 445

THE PROCESS OF SCIENCE
How Does Tropical Forest Fragmentation Affect Biodiversity? 446
Restoring Ecosystems 447
The Goal of Sustainable Development 448

EVOLUTION CONNECTION
Can Biophilia Save Biodiversity? 448



UNIT 5: Animal Structure and Function

21 Unifying Concepts of Animal Structure and Function 454

CHAPTER THREAD: CONTROLLING BODY TEMPERATURE

BIOLOGY AND SOCIETY
An Avoidable Tragedy 455

The Structural Organization of Animals **456**
Form Fits Function 456
Tissues 457
Organs and Organ Systems 461

Exchanges with the External Environment **464**

Regulating the Internal Environment **465**
Homeostasis 465
Negative and Positive Feedback 466
Thermoregulation 467

THE PROCESS OF SCIENCE
How Does a Python Warm Her Eggs? 468
Osmoregulation 468
Homeostasis in the Urinary System 469

EVOLUTION CONNECTION
Adaptations for Thermoregulation 471



22 Nutrition and Digestion 474

CHAPTER THREAD: CONTROLLING YOUR WEIGHT

BIOLOGY AND SOCIETY
The "Secret" to Shedding Pounds 475

Overview of Animal Nutrition **476**
Animal Diets 476
The Four Stages of Food Processing 476
Digestive Compartments 478

A Tour of the Human Digestive System **479**
System Map 479
The Mouth 479
The Pharynx 480
The Esophagus 480
The Stomach 480
The Small Intestine 482
The Large Intestine 484

Human Nutritional Requirements **485**
Food as Fuel 485
Food as Building Material 486
Decoding Food Labels 488

Nutritional Disorders **489**
Malnutrition 489
Obesity 490

THE PROCESS OF SCIENCE
Can a Gene Make You Fat? 490

EVOLUTION CONNECTION
Fat and Sugar Cravings 491



23 Circulation and Respiration 494

CHAPTER THREAD: ATHLETIC ENDURANCE

BIOLOGY AND SOCIETY
Avoiding "The Wall" 495

Unifying Concepts of Animal Circulation **496**
Open and Closed Circulatory Systems 496

The Human Cardiovascular System **497**
The Path of Blood 497
How the Heart Works 499
Blood Vessels 500
Blood 503

THE PROCESS OF SCIENCE
Live High, Train Low? 504
Cardiovascular Disease 506

Unifying Concepts of Animal Respiration **507**
The Structure and Function of Respiratory Surfaces 507

The Human Respiratory System **509**
The Structure and Function of the Human Respiratory System 510
Taking a Breath 511
The Role of Hemoglobin in Gas Transport 512
How Smoking Affects the Lungs 512

EVOLUTION CONNECTION
Evolving Endurance 513



24 The Body's Defenses 516

CHAPTER THREAD: HIV AND AIDS

BIOLOGY AND SOCIETY
The Elusive Search for an AIDS Vaccine 517

Innate Defenses **518**
External Innate Defenses 518
Internal Innate Defenses 519
The Lymphatic System 520

Adaptive Defenses **521**
Recognizing the Invaders 522

THE PROCESS OF SCIENCE
How Was HIV First Linked to AIDS? 523
Responding to the Invaders 524

Immune Disorders **528**
Allergies 528
Autoimmune Diseases 529
Immunodeficiency Diseases 529
AIDS 530

EVOLUTION CONNECTION
HIV Evolution 530

25 Hormones 534

CHAPTER THREAD: STEROID ABUSE

BIOLOGY AND SOCIETY
Sluggers and Steroids 535

Hormones: An Overview **536**

The Human Endocrine System **538**
The Hypothalamus and Pituitary Gland 540
The Thyroid and Parathyroid Glands 541
The Pancreas 543
The Adrenal Glands 544
The Gonads 546

THE PROCESS OF SCIENCE
Do 'Roids Cause Rage? 546

EVOLUTION CONNECTION
Steroids and Male Aggression 547

26 Reproduction and Development 550

CHAPTER THREAD: HIGH-TECH BABIES

BIOLOGY AND SOCIETY
Life after Death 551

Unifying Concepts of Animal Reproduction **552**
Asexual Reproduction 552
Sexual Reproduction 553

Human Reproduction **554**
Male Reproductive Anatomy 554
Female Reproductive Anatomy 555
Gametogenesis 556
The Female Reproductive Cycle 558

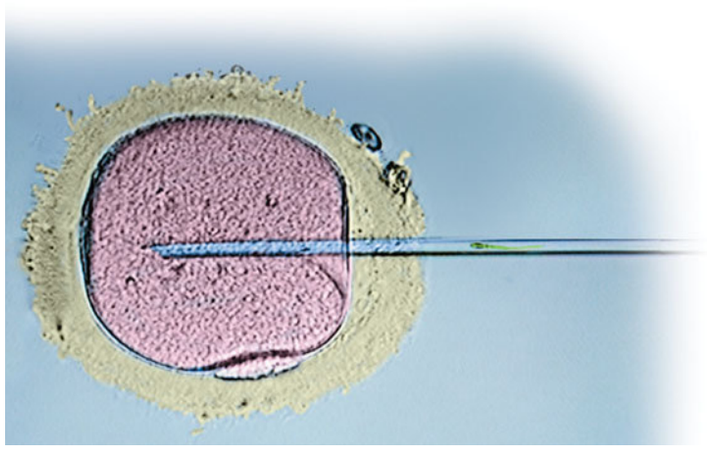
Reproductive Health **559**
Contraception 559
Sexually Transmitted Diseases 560

Human Development **562**
Fertilization 562
Basic Concepts of Embryonic Development 563
Pregnancy and Early Development 564
The Stages of Pregnancy 566
Childbirth 568

Reproductive Technologies **568**
Infertility 568
In Vitro Fertilization 569

THE PROCESS OF SCIENCE
Can Viable Embryos Be Identified? 569

EVOLUTION CONNECTION
The "Grandmother Hypothesis" 570



27 Nervous, Sensory, and Locomotor Systems 574

CHAPTER THREAD: EXTRAHUMAN SENSES

BIOLOGY AND SOCIETY
The Seismic Sense of Elephants 575

An Overview of Animal Nervous Systems **576**
Organization of Nervous Systems 576
Neurons 576
Sending a Signal through a Neuron 577
Passing a Signal from a Neuron to a Receiving Cell 579

The Human Nervous System: A Closer Look **581**
The Central Nervous System 581
The Peripheral Nervous System 582
The Human Brain 583

The Senses **587**
Sensory Input 587
Vision 588
Hearing 592

Locomotor Systems **593**
The Skeletal System 594
The Muscular System 596

THE PROCESS OF SCIENCE
How Do New Senses Arise? 598
Stimulus and Response: Putting It All Together 599

EVOLUTION CONNECTION
Seeing UV 599



UNIT 6: Plant Structure and Function

28 The Life of a Flowering Plant 604

CHAPTER THREAD: AGRICULTURE AND PEOPLE

BIOLOGY AND SOCIETY
The Buzz on Coffee Plants 605

The Structure and Function of a Flowering Plant **606**
Monocots and Dicots 606
Plant Organs: Roots, Stems, and Leaves 607
Plant Tissues and Tissue Systems 610
Plant Cells 611

Plant Growth **613**
Primary Growth: Lengthening 613
Secondary Growth: Thickening 614

THE PROCESS OF SCIENCE
What Happened to the Lost Colony of Roanoke? 616

The Life Cycle of a Flowering Plant **617**
The Flower 617
Overview of the Flowering Plant Life Cycle 618
Pollination and Fertilization 618
Seed Formation 619
Fruit Formation 620
Seed Germination 620

EVOLUTION CONNECTION
The Problem of the Disappearing Bees 621



29 The Working Plant 624

CHAPTER THREAD: THE INTERDEPENDENCE OF ORGANISMS

BIOLOGY AND SOCIETY
Planting Hope in the Wake of Disaster 625

How Plants Acquire and Transport Nutrients **626**
Plant Nutrition 626
From the Soil into the Roots 628
The Role of Bacteria in Nitrogen Nutrition 628
The Transport of Water 629
The Transport of Sugars 630

Plant Hormones **632**
Auxins 632

THE PROCESS OF SCIENCE
Do Chemical Signals Affect Plant Growth? 633
Ethylene 634
Cytokinins 634
Gibberellins 635
Abscisic Acid 635

Response to Stimuli **636**
Tropisms 636
Photoperiod 636

EVOLUTION CONNECTION
Plants, Mantises, and People 637

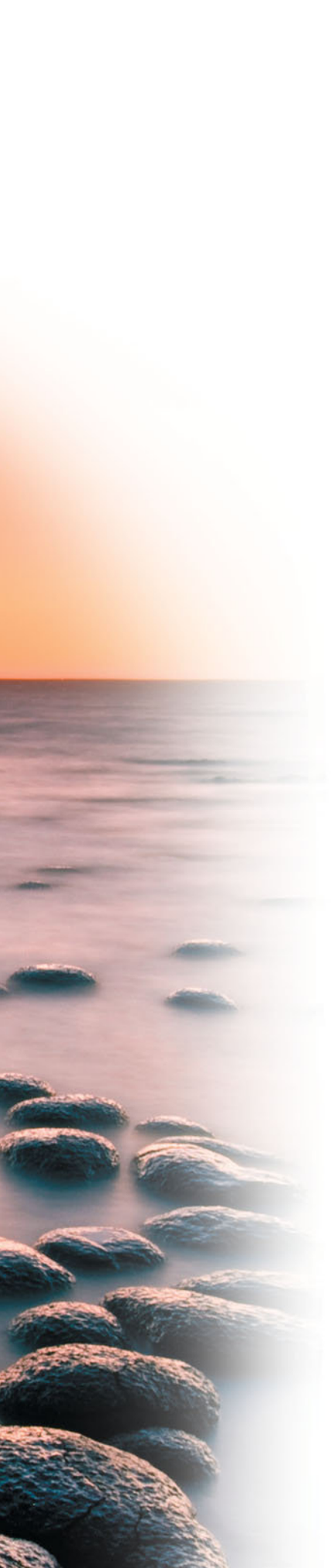


Appendices

A: Metric Conversion Table A-1
B: The Periodic Table A-3
C: Credits A-5
D: Self-Quiz Answers A-11

Glossary G-1

Index I-1



CHAPTER CONTENTS

Major Episodes in the History of Life 294
The Origin of Life 296
Prokaryotes 299
Protists 306

CHAPTER THREAD
How Life Began

BIOLOGY AND SOCIETY
Has Life Been Created in the Lab? 293
THE PROCESS OF SCIENCE
Can Biological Monomers Form Spontaneously? 297
EVOLUTION CONNECTION
The Origin of Multicellular Life 311



How Life Began BIOLOGY AND SOCIETY

Has Life Been Created in the Lab?

In *The Origin of Species*, Charles Darwin described the emergence of new species as a consequence of natural selection acting on existing species. But if you take his argument back to its logical start, you arrive at the ultimate mystery: How did life first arise on Earth?

Some biologists seek insight into this question through experiments on artificial systems. In 2010, a team led by Craig Venter (known for his role in sequencing the human genome—see Chapter 12) achieved a milestone in the burgeoning new field of synthetic biology. The researchers synthesized from scratch the entire genome of a small bacterium known as *Mycoplasma mycoides* and then transplanted the artificial genome into the cells of a closely related species called *Mycoplasma capricolum*. The newly installed genome took over the recipient cells and began cranking out *M. mycoides* proteins and reproducing to make more cells containing the synthetic *M. mycoides* genome. To verify that the synthetic genome was indeed in charge of the new cells, the researchers inserted several "watermarks" in its DNA, strings of bases encrypting messages that translate into English rather than amino acids. One of the watermarks, a quotation from physicist Richard Feynman, expresses one reason for pursuing this line of research: "What I cannot build, I cannot understand." Artificial life-forms may help answer fundamental questions about the origins of life in nature. Venter and others in the field also have more pragmatic—and potentially lucrative—goals. They hope to engineer artificial organisms that can be safely manipulated—a bacterial strain, for example, that might clean up toxic wastes or generate biofuels but be unable to survive outside specific conditions (so that it wouldn't spread out of control).

The Venter team's success at rebooting cells with a synthetic genome was a technical tour de force rather than an act of creation: The genome they built was plagiarized from existing life and transplanted to an off-the-shelf cell. Thus, the question, How did life begin? has yet to be answered. Although it may never be answered with certainty, the question continues to fascinate scientists. Accordingly, this chapter starts with a discussion of some of the key events in the history of life on Earth. We'll then discuss the origins, structures, and diversity of microbes (a term generally used to describe microscopic organisms), starting with the prokaryotes and then moving on to the protists.

Major Episodes in the History of Life

This chapter is the first of three that survey Earth's life-forms and their evolution. This section helps to set the stage by giving a brief overview of the major events in the history of life on Earth.

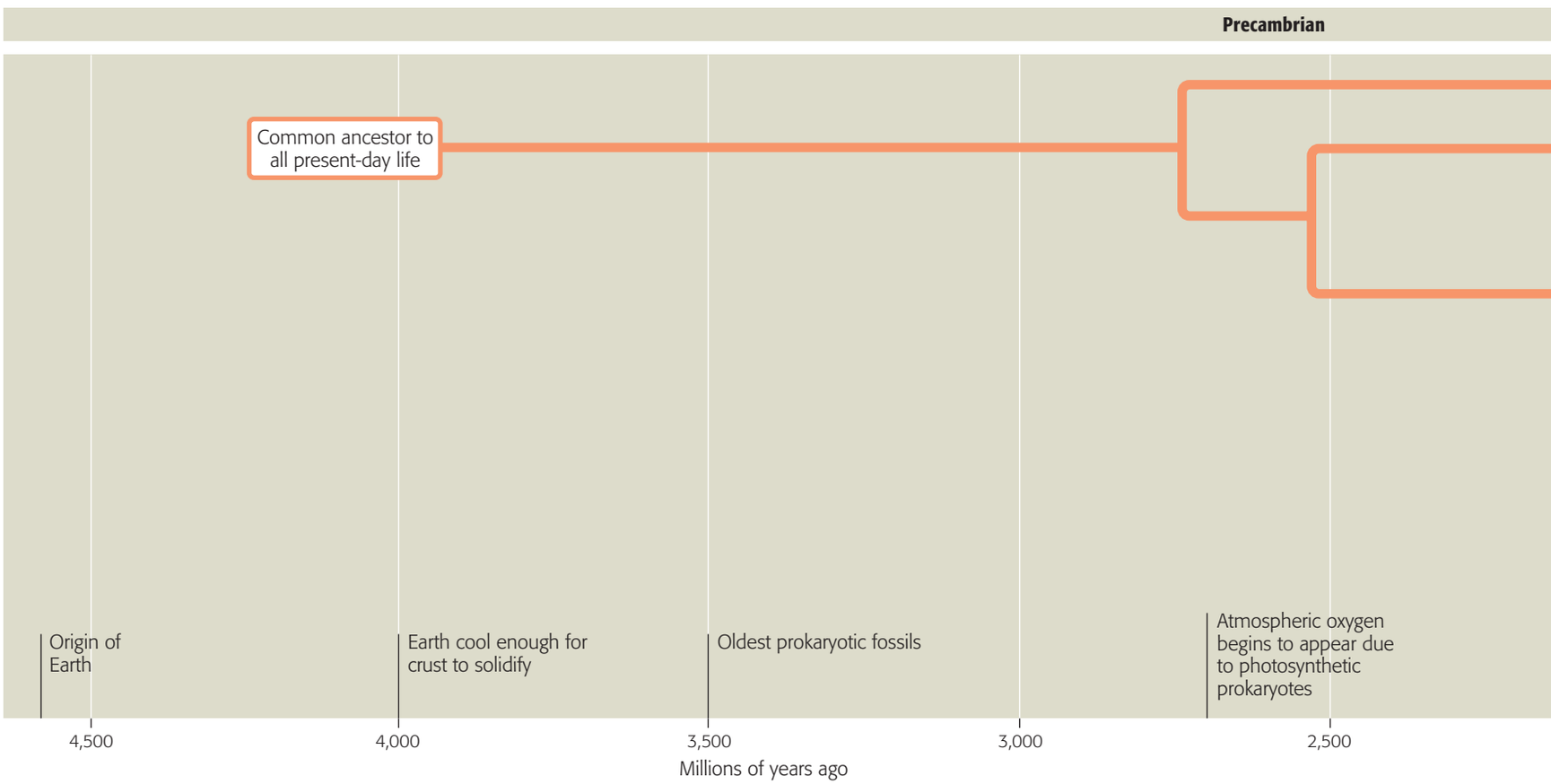
Life began when Earth was young. The planet formed about 4.6 billion years ago, and its crust began to solidify about 4 billion years ago. A few hundred million years later, by 3.5 billion years ago, Earth was already inhabited by a diversity of organisms **(Figure 15.1)**. Those earliest organisms were all **prokaryotes**, their cells lacking true nuclei. Within the next billion years, two distinct groups of prokaryotes—bacteria and archaea—diverged.

An oxygen revolution began about 2.7 billion years ago. Photosynthetic prokaryotes that split water molecules released oxygen gas, profoundly changing Earth's atmosphere (see the Evolution Connection section at the end of Chapter 6). The accumulation of O_2 in the atmosphere doomed many prokaryotic groups. Among the survivors, a diversity of metabolic modes evolved, including cellular respiration, which uses O_2 in extracting energy from food (see Chapter 6). All of this metabolic evolution occurred during the almost 2 billion years that prokaryotes had Earth to themselves.

The oldest eukaryotic fossils are about 2.1 billion years old. **Eukaryotes** are composed of one or more cells that contain nuclei and many other organelles absent in prokaryotic cells. The eukaryotic cell evolved from a prokaryotic community, a host cell containing even smaller prokaryotes. The mitochondria of our cells and those of every other eukaryote are descendants of those smaller prokaryotes, as are the chloroplasts of plants and algae.

The evolution of more complex cells launched a period of tremendous diversification of eukaryotic forms. These new organisms were the protists. Represented today by a great diversity of species, protists are mostly microscopic and unicellular. Examples you may recognize include algae, amoebas, and *Paramecium*.

The next great event in the evolution of life was multicellularity. As discussed in this chapter's Evolution Connection section, the first multicellular eukaryotes evolved at least 1.2 billion years ago as colonies of single-celled organisms. Their modern descendants



▼ Figure 15.1 Some major episodes in the history of life. The timing of events shown on this phylogenetic tree is based on fossil evidence and molecular analysis. (Review Figure 14.23 for a reminder of how to read and interpret phylogenetic trees.)

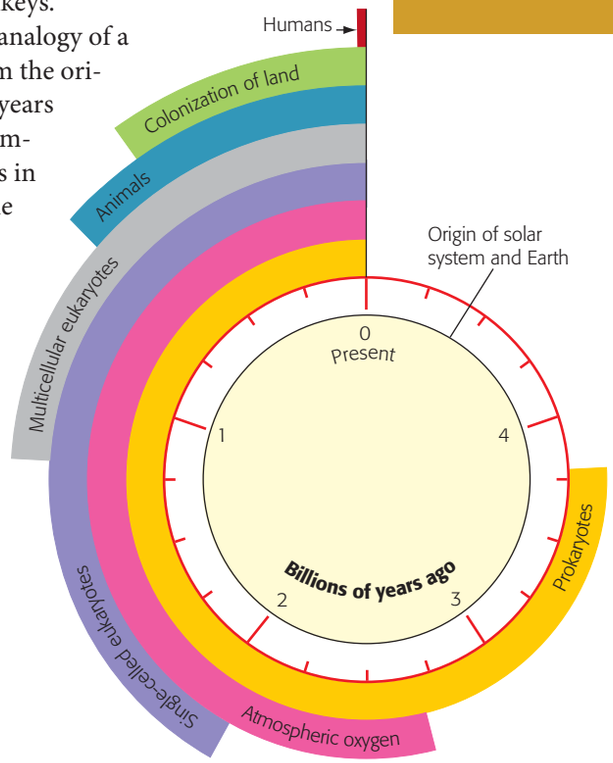
include multicellular protists, such as seaweeds. Other evolutionary branches stemming from the ancient protists gave rise to animals, fungi, and plants.

The greatest diversification of animals was the so-called Cambrian explosion. The Cambrian was the first period of the Paleozoic era, which began about 540 million years ago (see Table 14.1). The earliest animals lived in late-Precambrian seas, but they diversified extensively over a span of just 10 million years during the early Cambrian. In fact, all the major animal body plans—as well as all the major groups—had evolved by the end of that evolutionary eruption.

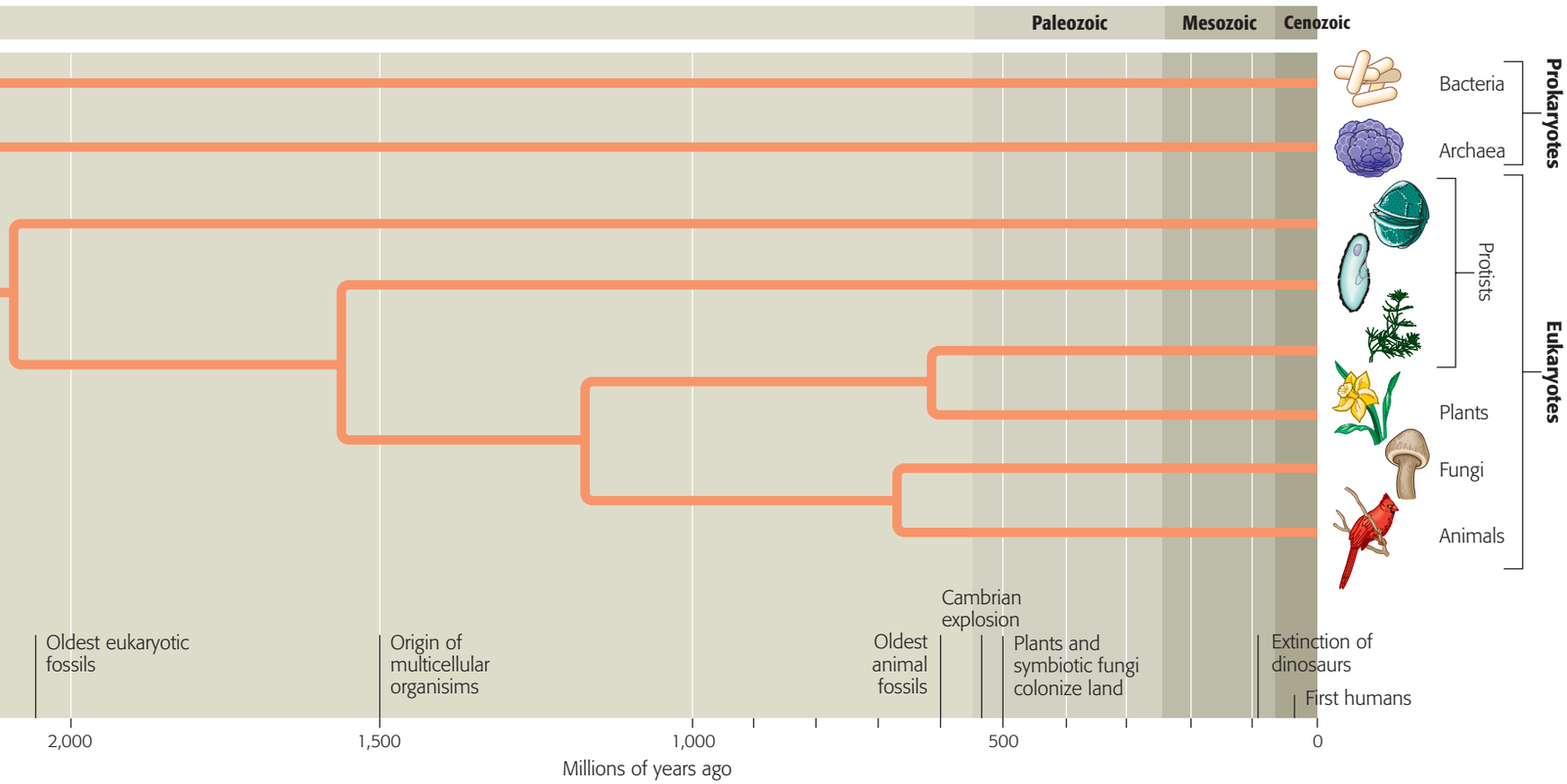
For over 85% of biological history—life's first 3 billion years—life was confined mostly to aquatic habitats. The colonization of land was a major milestone in the history of life. Plants and fungi together led the way about 500 million years ago. Plants transformed the landscape, creating new opportunities for all life-forms, especially herbivorous (plant-eating) animals and their predators.

The evolutionary venture onto land included vertebrate animals in the form of the first amphibians. These prototypes of today's frogs and salamanders descended from air-breathing fish with fleshy fins that could support the animal's weight on land. Further evolution by natural selection led to the appearance of reptiles and mammals. Among the mammals are the primates, the animal group that includes humans and their closest relatives, apes and monkeys.

Figure 15.2 uses the analogy of a clock ticking down from the origin of Earth 4.6 billion years ago to the present to summarize the major events in the history of life. As the figure makes clear, to trace the history of life on Earth, we must go back to the origin and diversification of microbes, starting with the prokaryotes (yellow band).



► **Figure 15.2 A clock analogy for the major events in the history of life on Earth.**



The Origin of Life

Although we'll never know for sure how life on Earth began, in this section we'll discuss hypotheses for the formation of the first life. Then we'll talk about its subsequent early evolution.

Resolving the Biogenesis Paradox

From the time of the ancient Greeks until well into the 1800s, it was commonly believed that life could regularly arise from nonliving matter, an idea called **spontaneous generation**. Many people believed, for instance, that flies arose from rotting meat and fish from ocean mud. Then, in 1862, experiments by Louis Pasteur confirmed what many others had suspected: All life today, including microbes, arises only by the reproduction of preexisting life. This "life-from-life" principle is called **biogenesis**.

But wait! If life always arises from previous life, then how could the first organisms arise? Although there is no evidence that spontaneous generation occurs today, it could have early in Earth's history, when conditions were very different. For instance, the O_2 in today's atmosphere is a corrosive agent that tends to disrupt chemical bonds, thereby preventing the formation of complex molecules—but O_2 wasn't present in the ancient atmosphere. And such energy sources as lightning, volcanic activity, and ultraviolet sunlight were all more intense on the early Earth than they are today. So life did not begin on a planet anything like the modern Earth, but on a young Earth that was a very different world **(Figure 15.3)**. Most biologists now think that chemical and physical processes in Earth's primordial environment could have led to very simple cells through a sequence of stages. Debate abounds about the nature of those stages. ☑

☑ CHECKPOINT

One reason why the spontaneous generation of life on Earth could not occur today is the abundance of _____ in our modern atmosphere.

Answer: oxygen (O_2)

A Four-Stage Hypothesis for the Origin of Life

According to one hypothesis for the origin of life, the first organisms were products of chemical evolution in four stages: (1) the abiotic (nonliving) synthesis of small organic molecules, such as amino acid and nucleotide monomers; (2) the joining of these small molecules into macromolecules, including proteins and nucleic acids; (3) the packaging of all these molecules into pre-cells, droplets with membranes that maintained an internal chemistry different from the surroundings; and (4) the origin of self-replicating molecules that eventually made inheritance possible. This is all speculative, of course, but what makes it a valid scientific hypothesis is that it leads to predictions that can be tested in the laboratory. Let's take a closer look at each of these four stages.

Stage 1: Abiotic Synthesis of Organic Monomers

This stage was the first to be extensively studied in the laboratory. We'll begin our investigation of chemical evolution with a breakthrough experiment that first brought this idea to the forefront of scientific thinking.



◄ Figure 15.3 An artist's rendition of Earth about 3 billion years ago. The pad-like objects in the scene represent colonies of prokaryotes known from the fossil record.

Can Biological Monomers Form Spontaneously?

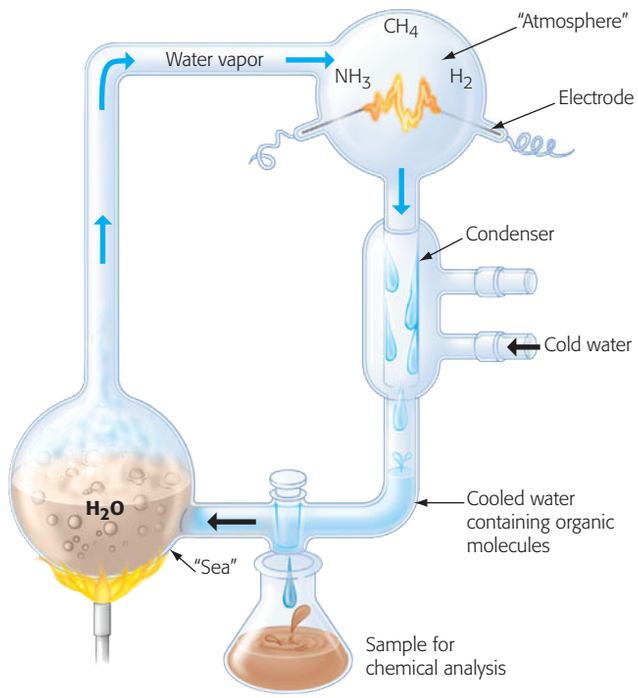
In 1953, University of Chicago scientist Harold Urey and his 23-year-old graduate student Stanley Miller conducted what is now considered a classic experiment. They began with the **observation** that modern biological macromolecules (DNA, protein, carbohydrates, and so on) are all composed of elements (primarily oxygen, hydrogen, carbon, and nitrogen) that were present in abundance on early Earth. This led to the **question**, Could biological molecules arise spontaneously under conditions like those on the early Earth? Miller and Urey began with the **hypothesis** that a closed system designed to simulate such conditions in the laboratory could produce biologically important organic molecules from inorganic ingredients.

Figure 15.4 shows the apparatus they created to test their hypothesis. A flask of warmed water simulated the primordial sea. An "atmosphere"—in the form of gases added to a reaction chamber—contained hydrogen gas (H_2), methane (CH_4), ammonia (NH_3), and water vapor (H_2O). To mimic the prevalent lightning of the early Earth, sparks were discharged into the chamber. A condenser cooled the atmosphere, causing water and any dissolved compounds to "rain" into the miniature "sea." Miller and Urey's **prediction** was that organic molecules would form and accumulate during this **experiment**.

Miller and Urey's **results** made front-page news. After the apparatus had run for a week, an abundance of organic molecules essential for life, including amino acids, the monomers of proteins, had collected in the "sea." These laboratory experiments, which have been repeated and extended by other scientists, support the idea that organic molecules could have arisen abiotically on the early Earth.

Researchers are also exploring other hypotheses about the origin of organic molecules. One hypothesis is based on observations of submerged volcanoes and deep-sea hydrothermal vents—gaps in Earth's crust where hot water and minerals gush into the deep oceans (see Figure 15.6). These undersea environments, rather than the atmosphere, may have provided the chemical resources for life's beginning. Another hypothesis for the origin of life omits the abiotic synthesis of organic monomers, proposing instead that meteorites provided a "starter set" of organic molecules. This hypothesis is based on observations of 4.5-billion-year-old meteorite fragments, which were found to contain a variety of organic molecules, including amino acids, sugars, and uracil (one of the building blocks of RNA).

▼ Figure 15.4 The abiotic production of organic molecules: a laboratory simulation of early-Earth chemistry.



Miller and Urey's experiment

Stage 2: Abiotic Synthesis of Polymers

Once small organic molecules were present, how were they linked together to form polymers such as proteins and nucleic acids without the help of enzymes and other cellular equipment? Researchers have brought about such polymerization by dripping solutions of organic monomers onto hot sand, clay, or rock. The heat vaporizes the water in the solutions and concentrates the monomers on the underlying material. Some of the monomers then spontaneously bond together to form polymers. On the early Earth, raindrops or waves may have splashed dilute solutions of organic monomers onto fresh lava or other hot rocks and then washed polypeptides and other polymers back into the sea. There they could accumulate in great quantities (since no life existed to consume them). ☑

☑ CHECKPOINT

What is the name of the chemical reaction whereby monomers are linked together into polymers? (*Hint*: Review Figure 3.4.)

Answer: *dehydration reaction*

Stage 3: Formation of Pre-Cells

According to the four-stage hypothesis, a key step in the origin of life was the isolation of a collection of abiotically created molecules within a membrane. We'll call these molecular aggregates pre-cells—not really cells, but molecular packages with some of the properties of life. Within a confined space, certain combinations of molecules could be concentrated and interact more efficiently. Furthermore, the internal environment of a pre-cell could differ from its surroundings.

Was there life before DNA?

Laboratory experiments demonstrate that pre-cells could have formed spontaneously from abiotically produced organic compounds (see Figure 5.20). Such pre-cells produced in the laboratory display some lifelike properties: They have a selectively permeable surface, can grow by absorbing molecules from their surroundings, and swell or shrink when placed in solutions of different salt concentrations.

Stage 4: Origin of Self-Replicating Molecules

Life is defined partly by the process of inheritance, which is based on self-replicating molecules. Today's cells store their genetic information as DNA. They transcribe the information into RNA and then translate RNA messages into specific enzymes and other proteins (see Figure 10.10). This mechanism of information flow probably emerged gradually through a series of small changes to much simpler processes.

What were the first genes like? One hypothesis is that they were short strands of RNA that replicated without the assistance of proteins. In laboratory experiments, short RNA molecules can assemble spontaneously from nucleotide monomers in the absence of enzymes **(Figure 15.5)**. The result is a population of RNA molecules, each with a random sequence of monomers. Some of the molecules self-replicate, but their success at this reproduction varies. What happens can be described as molecular evolution: The RNA varieties that replicate fastest increase their frequency in the population.

In addition to the experimental evidence, there is another reason the idea of RNA genes in the primordial world is plausible. Cells actually have RNAs that can act as enzymes; they are called ribozymes. Perhaps early ribozymes catalyzed their own replication. That would help with the "chicken and egg" paradox of which came first, enzymes or genes. Maybe the "chicken and egg" came together in the same RNA molecules. The molecular biology of today may have been preceded by an ancient "RNA world." ☑

From Chemical Evolution to Darwinian Evolution

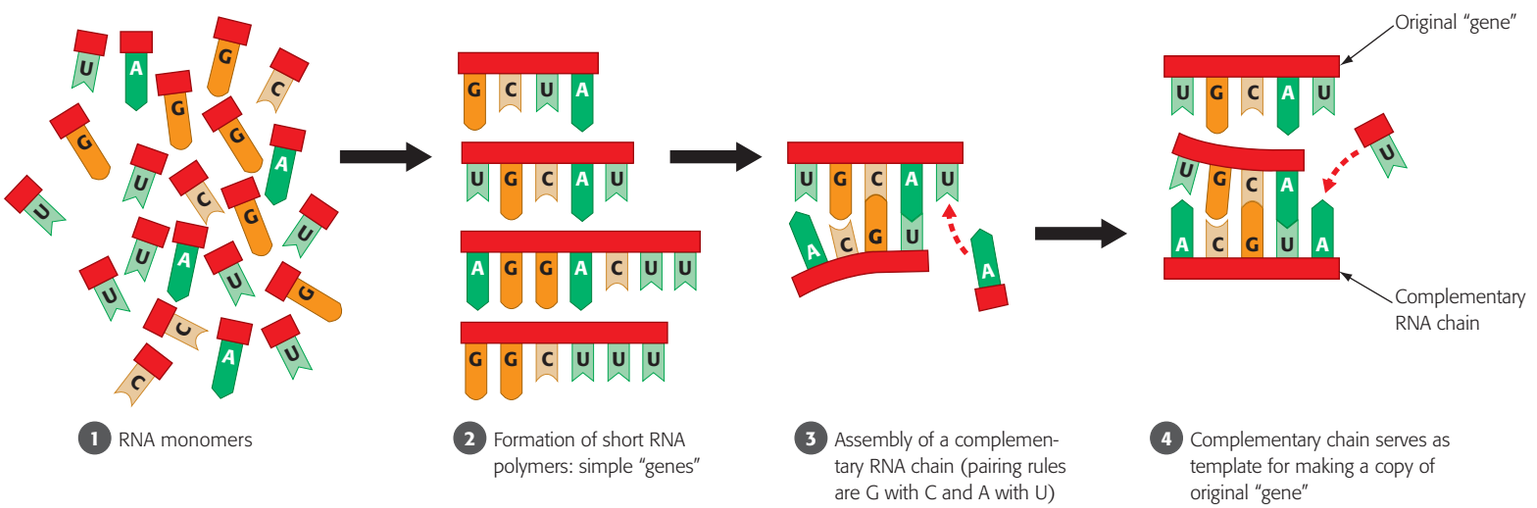
If pre-cells with self-replicating RNA (and later DNA) did form on a young Earth, they would be refined by natural selection. Mutations, errors in the copying of the "genes," would result in variation among the pre-cells. And the most successful of these pre-cells would grow, divide (reproduce), and continue to evolve. Of course, the gap between such pre-cells and even the simplest of modern cells is enormous. But with millions of years of incremental changes through natural selection, these molecular cooperatives could have become more and more cell-like. The point at which we stop calling them pre-cells and start calling them living cells is as fuzzy as our understanding of how life originated. But we do know that prokaryotes were already flourishing at least 3.5 billion years ago and that all branches of life arose from those ancient prokaryotes.

☑ CHECKPOINT

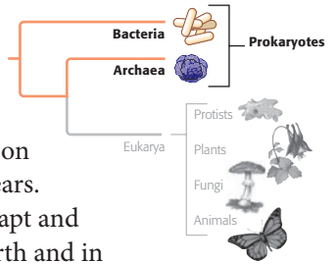
What are ribozymes? Why are they a logical step in the formation of life?

Answer: A ribozyme is an RNA molecule that functions as an enzyme. Ribozymes can perform some of the functions of both DNA and protein.

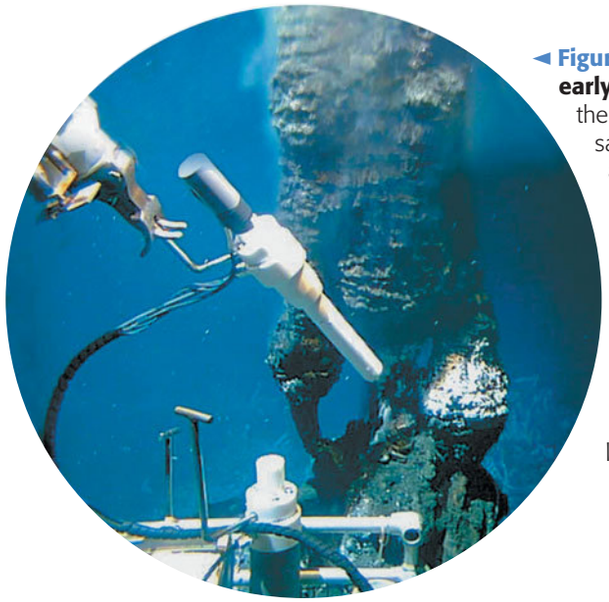
▼ Figure 15.5 Self-replication of RNA "genes."



Prokaryotes



The history of prokaryotic life is a success story spanning billions of years. Prokaryotes lived and evolved all alone on Earth for about 2 billion years. They have continued to adapt and flourish on an evolving Earth and in turn have helped to change the planet. In this section, you will study prokaryotic structure and function, diversity, effects on people, and ecological significance.

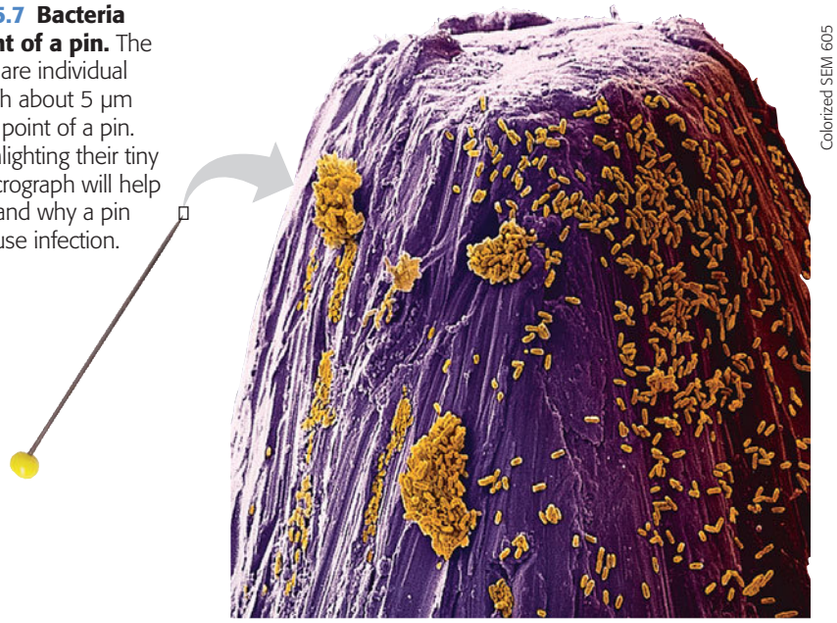


◄ **Figure 15.6 A window to early life?** An instrument on the research submarine *Alvin* samples the water around a hydrothermal vent more than 1.5 km (about a mile) below the ocean's surface. Prokaryotes that live near the vent use the emitted gases as an energy source. This environment, which is very dark, hot, and under high pressure, is among the most extreme in which life exists today.

They're Everywhere!

Today, prokaryotes are found wherever there is life, including in and on the bodies of multicellular organisms. The collective biological mass (biomass) of prokaryotes is at least ten times that of all eukaryotes. Prokaryotes also thrive in habitats too cold, too hot, too salty, too acidic, or too alkaline for any eukaryote **(Figure 15.6)**. Scientists are just beginning to investigate the extensive prokaryotic diversity in the oceans. Biologists have even discovered prokaryotes living on the walls of a gold mine 3.3 km (2 miles) below Earth's surface.

Though individual prokaryotes are small organisms **(Figure 15.7)**, they are giants in their collective impact on Earth and its life. We hear most about the relatively few species that cause illness. Bacterial infections are responsible for about half of all human diseases, including tuberculosis, cholera, many sexually transmitted infections, and certain types of food poisoning. However, prokaryotic life is much more than just a rogues' gallery. Benign or beneficial prokaryotes are far more common than harmful ones. For example, people have long used bacteria to produce various types of food, converting milk to cheese, yogurt, and sour cream. In addition, each of us harbors several hundred species of prokaryotes in and on our bodies. Many of the bacteria that live on our skin perform helpful housekeeping functions, such as decomposing dead skin cells. Some of our intestinal residents supply essential vitamins and enable us to obtain nutrition from food molecules that we couldn't otherwise digest. Bacteria also guard the body against microbial intruders.



► **Figure 15.7 Bacteria on the point of a pin.** The orange rods are individual bacteria, each about 5 µm long, on the point of a pin. Besides highlighting their tiny size, this micrograph will help you understand why a pin prick can cause infection.

Colorized SEM 605

Prokaryotes cause disease, so wouldn't we be better off without them?

It would be hard to overstate the importance of prokaryotes to the health of the environment. Prokaryotes living in the soil and at the bottom of lakes, rivers, and oceans help to decompose dead organisms and other organic waste material, returning vital chemical elements to the environment. If prokaryotes were to disappear, the chemical cycles that sustain life would come to a halt, and all forms of eukaryotic life would also be doomed. In contrast, prokaryotic life would undoubtedly persist in the absence of eukaryotes, as it once did for 2 billion years.

The Structure and Function of Prokaryotes

Prokaryotes have a cellular organization fundamentally different from that of eukaryotes. Whereas eukaryotic cells have a membrane-enclosed nucleus and numerous other membrane-enclosed organelles, prokaryotic cells lack these structural features (see Figures 4.4 and 4.5). And nearly all species of prokaryotes have cell walls exterior to their plasma membranes. Despite the simplicity of the cell structures, though, prokaryotes display an enormous range of diversity. In this section, you'll learn about aspects of their form, reproduction, and nutrition that help these organisms survive in their environments.

Prokaryotic Forms

Determining cell shape by microscopic examination is an important step in identifying a prokaryote. The micrographs in **Figure 15.8** show the three most common shapes. Spherical prokaryotic cells are called **cocci** (singular, *coccus*). Rod-shaped prokaryotes are called **bacilli** (singular, *bacillus*). A third prokaryotic cell shape is spiral or curved. These include spirochetes, different species of which cause syphilis and Lyme disease.

Although all prokaryotes are unicellular, the cells of some species usually exist as groups of two or more cells. For example, cocci that occur in clusters are called staphylococci. Other cocci, including the bacterium that causes strep throat, occur in chains; they are called streptococci. Some prokaryotes grow branching chains of cells **(Figure 15.9a)**. And some species even exhibit a simple division of labor among specialized types of cells **(Figure 15.9b)**. Among unicellular species, moreover, there are some giants that actually dwarf most eukaryotic cells **(Figure 15.9c)**.

▼ Figure 15.9 A diversity of prokaryotic shapes and sizes.

(a) Actinomycete. An actinomycete is a mass of branching chains of rod-shaped cells. These bacteria are common in soil, where they secrete antibiotics that inhibit the growth of other bacteria. Various antibiotic drugs, such as streptomycin, are obtained from actinomycetes.



Colorized SEM 4,800

LM 400



(b) Cyanobacteria. These photosynthetic cyanobacteria exhibit division of labor. The box highlights a cell that converts atmospheric nitrogen to ammonia, which can then be incorporated into amino acids and other organic compounds.

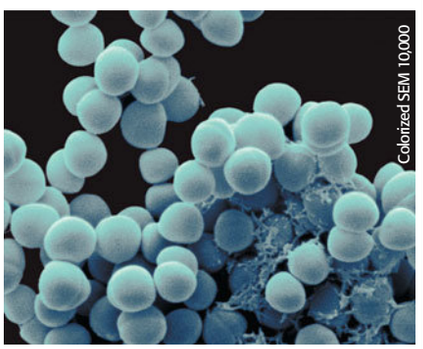
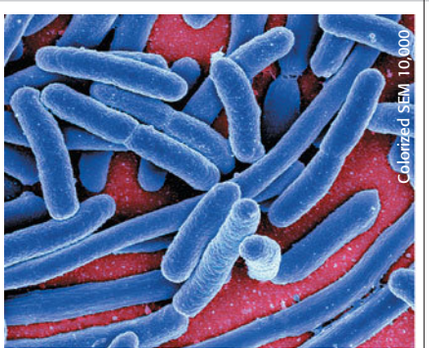
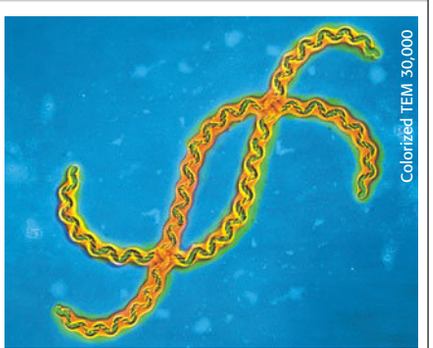
(c) Giant bacterium. The larger white blob in this photo is the marine bacterium *Thiomargarita namibiensis*. This prokaryotic cell is over 0.5 mm in diameter, about the size of the fruit fly's head below it.



LM 18

▼ Figure 15.8 Three common shapes of prokaryotic cells.

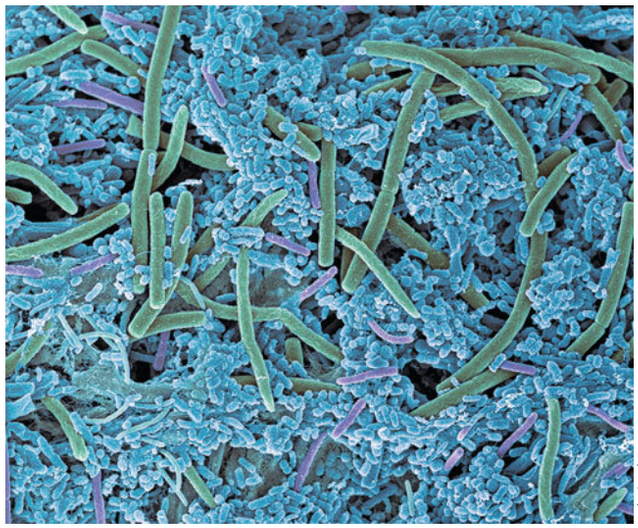
SHAPES OF PROKARYOTIC CELLS

Spherical (cocci)	Rod-shaped (bacilli)	Spiral
 Colorized SEM 10,000	 Colorized SEM 10,000	 Colorized TEM 30,000

About half of all prokaryotic species are mobile. Many of those that travel have one or more flagella that propel the cells away from unfavorable places or toward more favorable places, such as nutrient-rich locales.

In many natural environments, prokaryotes attach to surfaces in a highly organized colony called a **biofilm**. A biofilm may consist of one or several species of prokaryotes, and it may include protists and fungi as well. As a biofilm becomes larger and more complex, it develops into a "city" of microbes. Communicating by chemical signals, members of the community engage in division of labor, including defense against invaders, among other activities.

Biofilms can form on almost any type of surface, such as rocks, organic material (including living tissue), metal, and plastic. A biofilm known as dental plaque **(Figure 15.10)** can cause tooth decay. Biofilms are common among bacteria that cause disease in humans. For instance, ear infections and and urinary tract infections are often the result of biofilm-forming bacteria. Biofilms of harmful bacteria can also form on implanted medical devices such as catheters, replacement joints, or pacemakers. The structure of biofilms makes these infections especially difficult to defeat. Antibiotics may not be able to penetrate beyond the outer layer of cells, leaving much of the community intact.



Colorized SEM 6,000

◄ Figure 15.10 Dental plaque, a biofilm that forms on teeth.

Prokaryotic Reproduction

Many prokaryotes can reproduce at a phenomenal rate if conditions are favorable. The cells copy their DNA almost continuously and divide again and again by the process of **binary fission**. Dividing by binary fission, a single cell becomes 2 cells, which then become 4, 8, 16, and so on. Some species can produce a new generation in only 20 minutes under optimal conditions. If reproduction continued unchecked at this rate, a single prokaryote could give rise to a colony outweighing Earth in only three days! Also, each time DNA is replicated prior to binary fission, spontaneous mutations occur. As a result, rapid reproduction generates a great deal of genetic variation in a prokaryotic population. If the environment changes, an individual that possesses a beneficial gene can quickly take advantage of the new conditions. For example, exposure to antibiotics may select for antibiotic resistance in a bacterial population (see the Evolution Connection at the end of Chapter 4).

Fortunately, few prokaryotic populations can sustain exponential growth for long. Environments are usually limiting in resources such as food and space. Prokaryotes also produce metabolic waste products that may eventually pollute the colony's environment. Still, you can understand why certain bacteria can make you sick so soon after infection or why food can spoil so rapidly.

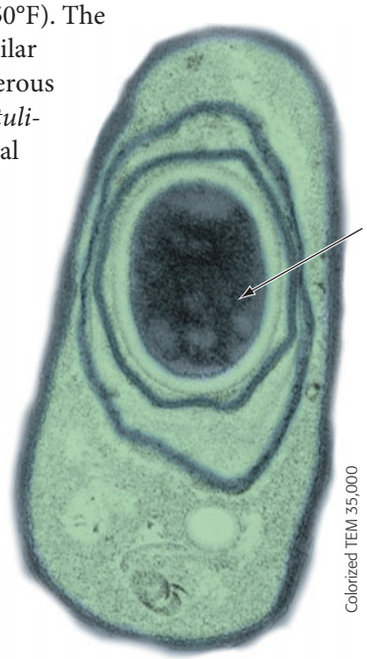
Refrigeration retards food spoilage not because the cold kills bacteria, but because most microorganisms reproduce very slowly at such low temperatures.

Some prokaryotes can survive during very harsh conditions by forming specialized cells called endospores. An **endospore** is a thick-coated, protective cell produced within the prokaryotic cell when the prokaryote is exposed to unfavorable conditions **(Figure 15.11)**. The endospore can survive all sorts of trauma and extreme heat or cold. Not even boiling water kills most of these resistant cells. And when the environment becomes more hospitable, the endospore can absorb water and resume growth. To ensure that all cells, including endospores, are killed when laboratory equipment is sterilized, microbiologists use an appliance called an autoclave, a pressure cooker that uses high-pressure steam at a temperature of 121°C (250°F). The food-canning industry employs similar methods to kill endospores of dangerous soil bacteria such as *Clostridium botulinum*, the cause of the potentially fatal disease botulism. ☑

☑ CHECKPOINT

1. Using a microscope, how could you distinguish the cocci that cause staph infections from those that cause strep throat?
2. Why do microbiologists autoclave their laboratory instruments and glassware rather than just washing them in very hot water?

Answers: **1.** *by the arrangement of the cell aggregates: grapelike clusters for staphylococcus and chains of cells for streptococcus* **2.** *to kill bacterial endospores, which can survive boiling water*



Colorized TEM 35,000

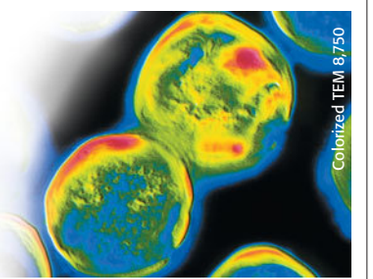
► Figure 15.11 An endospore in an anthrax bacterium. This prokaryote is *Bacillus anthracis*, the notorious bacterium that produces the disease called anthrax in cattle, sheep, and people. There are actually two cells here, one inside the other. The outer cell produced the specialized dormant inner cell, the endospore.

Prokaryotic Nutrition

When classifying diverse organisms, biologists often use the phrase "mode of nutrition" to describe how an organism obtains energy and carbon, the two main resources needed for synthesizing organic compounds. Species that obtain energy from light are called phototrophs, while species that obtain energy from environmental chemicals are called chemotrophs. Species that obtain carbon from the inorganic compound carbon dioxide (CO_2) are called autotrophs, while species that obtain carbon from at least one organic nutrient—the sugar glucose, for instance—are called heterotrophs. We can combine energy source (phototroph versus chemotroph) and carbon source (autotroph versus heterotroph) to group all organisms according to the four major modes of nutrition shown in **Figure 15.12**. Two of these modes—photoautotrophs (such as most plants), and chemoheterotrophs (such as most animals)—are dominant among multicellular organisms. The other two modes are used only by certain prokaryotes. ☑

► **Figure 15.12**
Modes of nutrition.

MODES OF NUTRITION

Carbon source	Energy source: Light	Energy source: Chemical
CO_2	**Photoautotrophs** These organisms are photosynthesizers that use light to drive the synthesis of organic compounds from CO_2. Photoautotrophs include plants and algae.  *Elodea*, an aquatic plant	**Chemoautotrophs** These organisms extract energy from inorganic substances such as ammonia, NH_3. All chemoautotrophs are prokaryotes.  Bacteria from a hot spring
Organic compounds	**Photoheterotrophs** These organisms harness energy from light but must obtain carbon in organic form. All photoheterotrophs are prokaryotes.  *Rhodopseudomonas*	**Chemoheterotrophs** These organisms consume organic molecules for both energy and carbon. Chemoheterotrophs include some prokaryotes and protists and all fungi and animals.  Kingfisher with prey

☑ CHECKPOINT

A bacterium requires only water and the amino acid methionine to grow and lives in very deep caves where no light penetrates. Based on its mode of nutrition, this species would be classified as a _____.

Answer: *chemoheterotroph*

The Two Main Branches of Prokaryotic Evolution: Bacteria and Archaea

By comparing diverse prokaryotes at the molecular level, biologists have identified two major branches of prokaryotic evolution: **bacteria** and **archaea**. Thus, life is organized into three domains—**Bacteria**, **Archaea**, and **Eukarya** (review Figure 14.25). Although bacteria and archaea have prokaryotic cell organization in common, they differ in many structural and physiological characteristics. Some of these differences suggest that archaea are more closely related to eukaryotes than they are to bacteria. In this section, we'll focus on the special characteristics of archaea before turning our attention to bacteria.

The term *archaea* ("ancient") refers to the antiquity of this group's origin from the earliest cells. Even today, many species of archaea inhabit extreme environments, such as hot springs and salt ponds. Few other modern organisms (if any) can survive in some of these environments, which may resemble habitats on the early Earth.

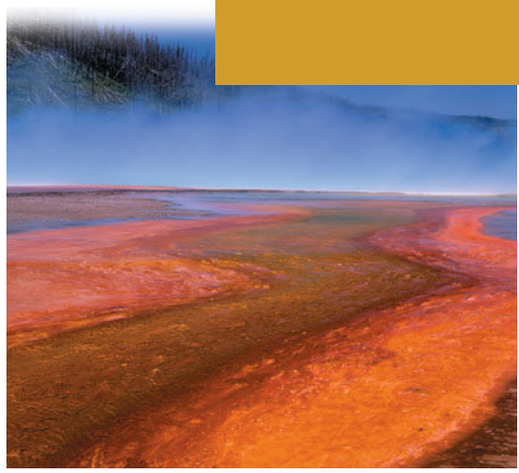
Biologists refer to some archaea as "extremophiles," meaning "lovers of the extreme." There are extreme halophiles ("salt lovers"), archaea that thrive in such environments as Utah's Great Salt Lake, the Dead Sea, and seawater-evaporating ponds used to produce salt

(Figure 15.13a). There are also extreme thermophiles ("heat lovers") that live in very hot water (Figure 15.13b); some archaea even populate the deep-ocean vents that gush water hotter than 100°C (212°F), such as the one shown in Figure 15.6. Also among the archaea are the methanogens, which live in anaerobic (oxygen-free) environments and give off methane as a waste product. They are abundant in the mud at the bottom of lakes and swamps. You may have seen methane, also called marsh gas, bubbling up from a swamp. Great numbers of methanogens also inhabit the digestive tracts of animals. In humans, intestinal gas is largely the result of their metabolism. More importantly, methanogens aid digestion in cattle, deer, and other animals that depend heavily on cellulose for their nutrition. Normally, bloating does not occur in these animals because they regularly expel large volumes of gas produced by the methanogens. (And that may be more than you wanted to know about these gas-producing microbes!)

▼ **Figure 15.13 Archaeal "extremophiles."**



(a) Salt-loving archaea. This is an aerial photo of commercial salt-producing ponds at the edge of San Francisco Bay. The colors of the ponds result from dense growth of the harmless prokaryotes that thrive when the salinity of the water reaches five to eight times that of seawater.



(b) Heat-loving archaea. In this photo, you can see orange colonies of heat-loving prokaryotes growing near Grand Prismatic Spring in Yellowstone National Park, Wyoming.

Bacteria and Disease

In this section, we'll consider some aspects of disease-causing bacteria. Keep in mind, though, that only a minority of prokaryotes are harmful—many more are beneficial.

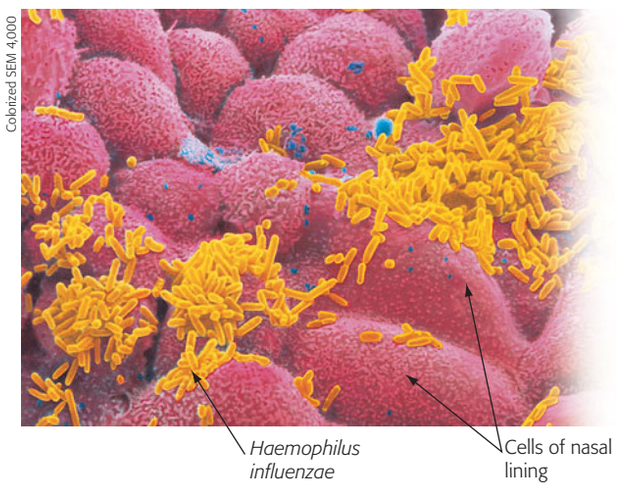
Bacteria That Cause Disease

We are constantly exposed to bacteria, some of which are potentially harmful (Figure 15.14). Bacteria and other organisms that cause disease are called **pathogens**. We're healthy most of the time because our body's defenses check the growth of pathogen populations. Occasionally, the balance shifts in favor of a pathogen, and we become ill. Even some of the bacteria that are normal residents of the human body can make us sick when our defenses have been weakened by poor nutrition or a viral infection.

Most pathogenic bacteria cause disease by producing a poison—either an exotoxin or an endotoxin. **Exotoxins** are proteins that bacterial cells secrete into their environment. For example, *Staphylococcus aureus* (abbreviated *S. aureus*) produces several exotoxins. Although *S. aureus* is commonly found on the skin and in the nasal passages, if it enters the body through a wound, it can cause serious disease. One of its exotoxins causes layers of skin to slough off ("flesh-eating disease"); another can produce a potentially deadly disease called toxic shock syndrome. Food may also be contaminated with *S. aureus* exotoxins, which are so potent that a millionth of a gram causes vomiting and diarrhea.

Endotoxins are chemical components of the outer membrane of certain bacteria. All endotoxins induce the same general symptoms: fever, aches, and sometimes a dangerous drop in blood pressure (septic shock). Septic shock triggered by an endotoxin of the pathogen that causes bacterial meningitis can kill a healthy person in a matter of days, or even hours. Because the bacteria are easily transmitted among people living in close contact, many colleges require students to be vaccinated against this disease. Other examples of endotoxin-producing bacteria include the species of *Salmonella* that cause food poisoning and typhoid fever.

How do bacteria make us sick?



◄ **Figure 15.14 Bacteria that cause pneumonia.** *Haemophilus influenzae*, shown here on cells lining the interior of a human nose, causes pneumonia and other lung infections, which kill about 4 million people worldwide per year. Most victims are children in less industrialized countries, where malnutrition lowers resistance to all pathogens.

During the last century, following the discovery that "germs" cause disease, the incidence of bacterial infections declined, particularly in more industrialized nations. Sanitation is generally the most effective way to prevent bacterial disease. The installation of water treatment and sewage systems continues to be a public health priority throughout the world. Antibiotics have been discovered that can cure most bacterial diseases. However, resistance to widely used antibiotics has evolved in many of these pathogens. (For example, Figure 4.7 explains antibiotic-resistant *S. aureus*.)

In addition to sanitation and antibiotics, a third defense against bacterial disease is education. A case in point is Lyme disease, which is caused by a spirochete bacterium carried by ticks **(Figure 15.15)**. Disease-carrying ticks live on deer and field mice but also bite humans. Lyme disease usually starts as a red rash shaped like a bull's-eye around a tick bite. Antibiotics can cure the disease if administered within a month of exposure. If untreated, Lyme disease can cause debilitating arthritis, heart disease, and nervous system disorders. So far, the best defense is public education about avoiding tick bites and the importance of seeking treatment if a rash develops. The Centers for Disease Control and Prevention recommends that you avoid vegetation in tick-infested areas, wear light-colored clothing when walking through brush so that you can easily see any ticks, and use an appropriate insect repellent. ☑

☑ CHECKPOINT

How can an exotoxin be harmful even after bacteria are killed?

Answer: Exotoxins are secreted poisons that can remain harmful even when the bacteria that secrete them are gone.

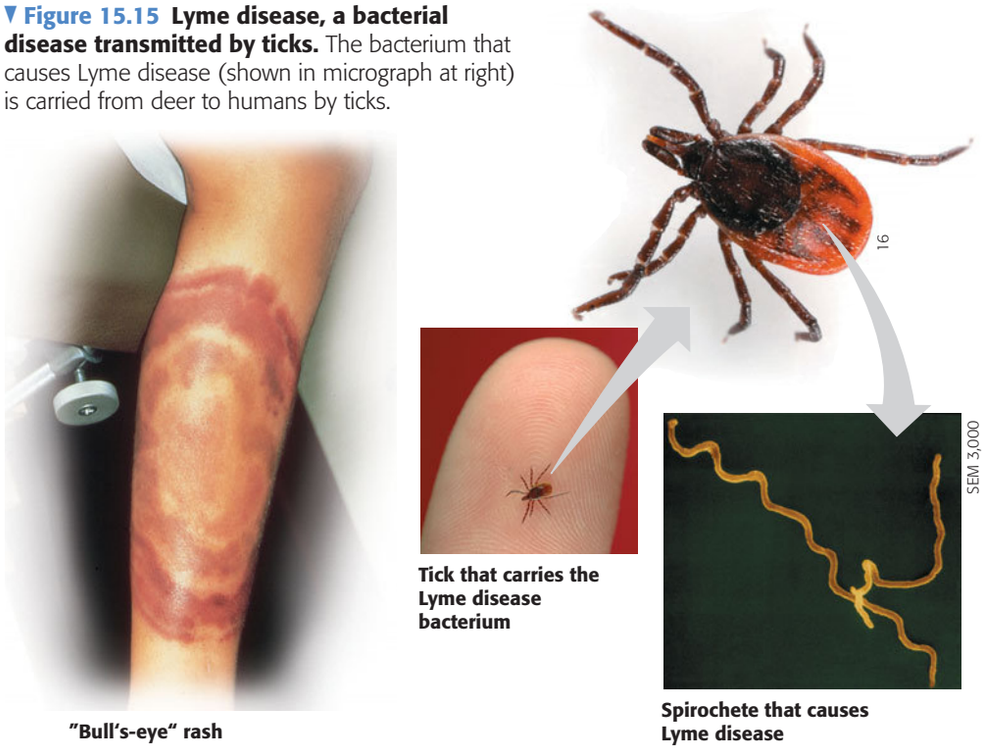
Biological Weapons

In October 2001, endospores of the bacterium that causes anthrax (see Figure 15.11) were mailed to members of the news media and the U.S. Senate. When anthrax endospores enter the lungs, they germinate, and the bacteria multiply, producing an exotoxin that eventually accumulates to lethal levels in the blood. Although the bacteria can be killed by certain antibiotics, the antibiotics don't eliminate the toxin already in the body. As a result, inhalation anthrax has a very high death rate. The attacks in 2001, which resulted in five deaths, raised public awareness of the potential for biological agents such as viruses and bacteria to be used as weapons.

The bacterium that causes plague is also among the biological agents that are considered the highest-priority threats. Plague bacteria are carried by rodents in many parts of the world and are transmitted by fleas. People contract the disease when they are bitten by infected fleas. When diagnosed in time, plague can be treated by antibiotics. In the untreated bubonic form of plague, egg-size swellings called buboes grow in the armpits, groin, and neck, and black blotches appear where the bacteria proliferate in clots under the skin **(Figure 15.16)**. If bacteria spill into the bloodstream, death from the bacterial toxins is certain. In the pneumonic form of plague, the bacteria infect cells in the lungs, becoming airborne as the disintegrating lung tissue is coughed out in droplets. As a result, pneumonic plague is easily transmitted from person to person and can become epidemic, the worst scenario for an attack by biological weapons.

Another bacterium considered to have dangerous potential as a weapon is *Clostridrium botulinum*. Unlike other biological agents, the weapon form of *C. botulinum* is the exotoxin it produces, botulinum, rather than the living microbes. Botulinum, which blocks transmission of the nerve signals that cause muscle contraction, is the deadliest poison on earth. Thirty grams of pure toxin, a bit more than an ounce, could kill every person in the United States.

▼ Figure 15.15 Lyme disease, a bacterial disease transmitted by ticks. The bacterium that causes Lyme disease (shown in micrograph at right) is carried from deer to humans by ticks.



▼ Figure 15.16 Swellings characteristic of bubonic plague.



The Ecological Impact of Prokaryotes

Pathogenic bacteria are in the minority among prokaryotes. Far more common are species that are essential to our well-being, either directly or indirectly. Let's turn our attention now to the vital role that prokaryotes play in sustaining the biosphere.

Prokaryotes and Chemical Recycling

Not too long ago, the atoms making up the organic molecules in your body were part of inorganic compounds found in soil, air, and water, as they will be again. Life depends on the recycling of chemical elements between the biological and physical components of ecosystems. Prokaryotes play essential roles in these chemical cycles. For example, nearly all the nitrogen that plants use to make proteins and nucleic acids comes from prokaryotic metabolism in the soil. In turn, animals get their nitrogen compounds from plants.

Another vital function of prokaryotes, mentioned earlier in the chapter, is the breakdown of organic wastes and dead organisms. Prokaryotes decompose organic matter and, in the process, return elements to the environment in inorganic forms that can be used by other organisms. If it were not for such decomposers, carbon, nitrogen, and other elements essential to life would become locked in the organic molecules of corpses and waste products. (You'll learn more about the role that prokaryotes play in chemical cycling in Chapter 20.)

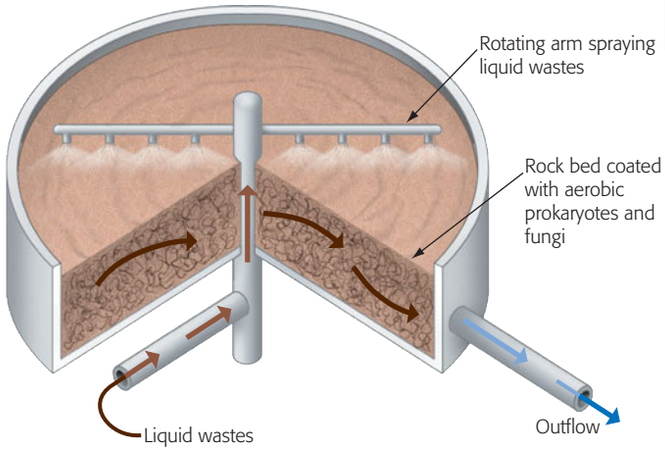
Prokaryotes and Bioremediation

People have put the metabolically diverse prokaryotes to work in cleaning up the environment. **Bioremediation** is the use of organisms to remove pollutants from water, air, or soil. One example of bioremediation is the use of prokaryotic decomposers to treat our sewage. Raw sewage is first passed through a series of screens and shredders, and solid matter settles out from the liquid waste. This solid matter, called sludge, is then gradually added to a culture of anaerobic prokaryotes, including both bacteria and archaea. The microbes decompose the organic matter in the sludge, converting it to material that can be used as landfill or fertilizer. The liquid wastes may then be passed through a trickling filter system consisting of a long horizontal bar that slowly rotates, spraying liquid wastes onto a bed of rocks (**Figure 15.17**). Aerobic prokaryotes and fungi growing on the rocks remove much of the organic matter from the liquid. The outflow from the rock bed is then sterilized and released back into the environment.

Bioremediation has also become an important tool for cleaning up toxic chemicals released into the soil and water by industrial processes. Naturally occurring prokaryotes capable of degrading pollutants such as oil, solvents, and pesticides are often present in contaminated soil, but their activity is limited by environmental factors such as nutrient availability. In **Figure 15.18**, workers are spraying an oil-polluted beach in Alaska with fertilizers to stimulate soil bacteria to speed up the breakdown of oil. Chemical dispersants were used in the massive Gulf of Mexico oil spill in 2010. Like detergents that help clean greasy dishes, these chemicals break oil into smaller droplets that offer more surface area for microbial attack. Prokaryotes are also helping to decontaminate old mining sites where the soil and water are laced with heavy metals and other poisons. We are just beginning to explore the great potential that prokaryotes offer for bioremediation. In the future, genetically engineered microbes may be put to work cleaning up the wide variety of toxic waste products that continue to accumulate in our landscapes and landfills.

Can prokaryotes clean up our environmental messes?

The various modes of nutrition and metabolic pathways we find in organisms living today are all variations on themes that evolved in prokaryotes during their long reign as Earth's exclusive inhabitants. The subsequent breakthroughs in evolution were mostly structural, including the origin of the eukaryotic cell and the diversification of the protists. ☑



▲ **Figure 15.17 Putting microbes to work in sewage treatment facilities.** This is a trickling filter system, which uses bacteria, archaea, and fungi to treat liquid wastes after sludge is removed.

☑ CHECKPOINT

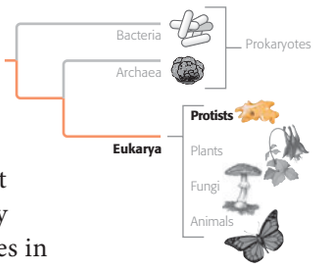
How do bacteria help restore the atmospheric CO_2 required by plants for photosynthesis?

Answer: By decomposing the organic molecules of dead organisms and organic refuse such as leaf litter, bacteria release carbon from the organic matter in the form of CO_2.

▼ **Figure 15.18 Treatment of an oil spill in Alaska.** A worker is spraying fertilizers onto an oil-soaked beach. The fertilizers stimulate growth of naturally occurring bacteria that initiate the breakdown of the oil.



Protists



Anton van Leeuwenhoek, an early Dutch microscopist, was the first person to describe the microbial world: "No more pleasant sight has met my eye than this of so many thousands of living creatures in one small drop of water," he wrote more than three centuries ago. The diverse creatures van Leeuwenhoek saw as he peered through his microscope are called protists. The term **protists** is a bit of a catch-all category that includes all eukaryotes that are not fungi, animals, or plants. Most, but not all, are unicellular. Because their cells are eukaryotic, even the simplest protists are much more complex than any prokaryote.

The fossil record indicates that the first eukaryotes evolved from prokaryotes around 2 billion years ago. These primal eukaryotes were not only the predecessors of the great variety of modern protists; they were also ancestral to all other eukaryotes—plants, fungi, and animals. So before we sample the wide diversity of present-day protists, let's look at how it all began.

☑ CHECKPOINT

Which organelles of eukaryotic cells probably descended from endosymbiotic bacteria?

Answer: mitochondria and chloroplasts

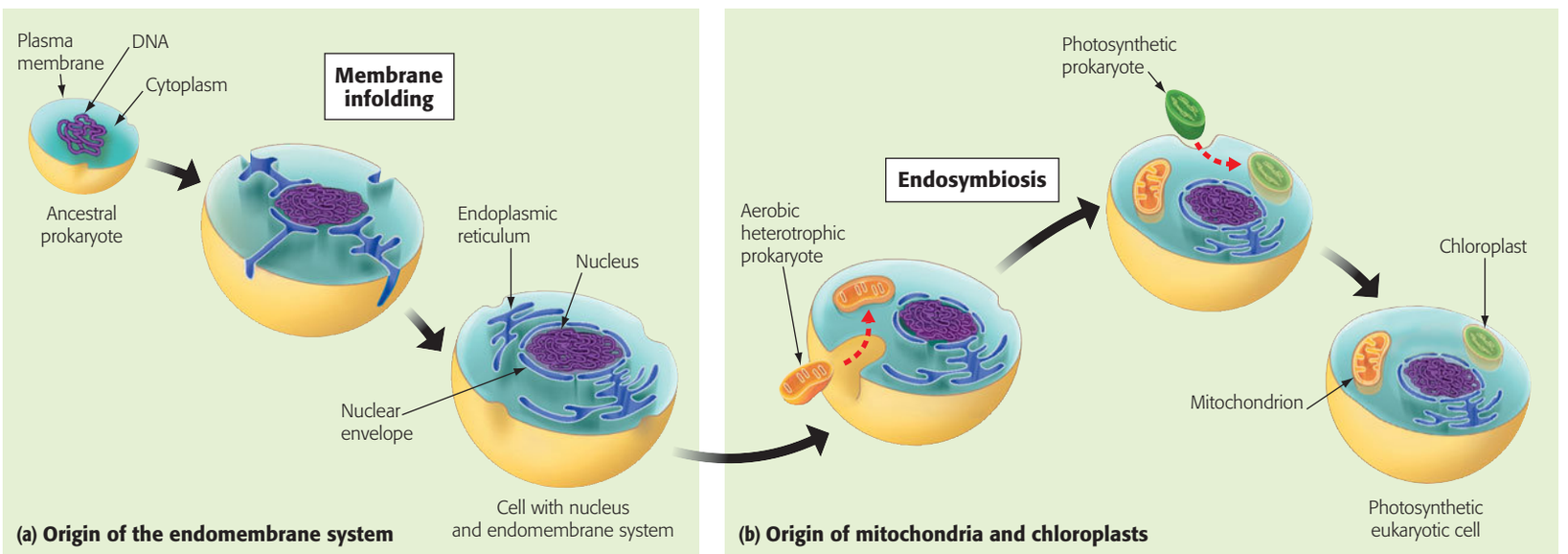
The Origin of Eukaryotic Cells

Membrane-enclosed organelles are a distinguishing feature of eukaryotic cells. How did these complex cells arise from prokaryotic ancestors? A widely accepted theory is that eukaryotic cells evolved through a combination of two processes. In one process, the eukaryotic cell's endomembrane system—all of the membrane-enclosed organelles except mitochondria and chloroplasts (review Figure 4.18)—evolved from inward folds of the plasma membrane of a prokaryotic cell **(Figure 15.19a)**.

A second process, called endosymbiosis, generated mitochondria and chloroplasts. **Symbiosis** ("living together") is a close association between organisms of two or more species, and **endosymbiosis** refers to one species living inside another host species. Chloroplasts and mitochondria seem to have evolved from small symbiotic prokaryotes (symbionts) that established residence within other, larger host prokaryotes **(Figure 15.19b)**. These small prokaryotes may have gained entrance to the larger cell as undigested prey or as internal parasites. In a world that was becoming increasingly aerobic, a cell that was itself an anaerobe would have benefited from aerobic endosymbionts that turned the oxygen to advantage. And a heterotrophic host could derive nourishment from photosynthetic endosymbionts. As the host and endosymbionts became increasingly interdependent, they would have become single organisms with inseparable parts.

Extensive evidence supports the endosymbiosis model. Present-day mitochondria and chloroplasts are similar to prokaryotic cells in a number of ways. For example, both types of organelles contain small amounts of DNA, RNA, and ribosomes that resemble prokaryotic versions more than eukaryotic ones. They also replicate their own DNA and reproduce within the cell by a process resembling the binary fission of prokaryotes. ☑

▼ Figure 15.19 A two-stage hypothesis for the evolution of eukaryotes through endosymbiosis.



The Diversity of Protists

The origin of the eukaryotic cell made more complex organisms possible, and a vast variety of protists evolved. Given that the term *protist* is a catch-all category, it shouldn't be surprising that the protists are a mixed bag of organisms. They are all eukaryotes, but they are so diverse that it is hard to name any other general characteristics about them. Biologists used to classify all protists in a kingdom called Protista, but recent molecular and cellular studies have shaken the foundations of protist taxonomy. It is now clear that there are multiple clades of protists, with some lineages more closely related to plants, fungi, or animals than they are to other protists. While our knowledge of the evolutionary relationships among these diverse groups remains incomplete, *protists* is still a convenient term to refer to eukaryotes that are not plants, animals, or fungi.

▼ Figure 15.21 A diversity of protists in a drop of pond water.



LM 240

One mark of protist diversity is the variety of ways they obtain their nutrition. Some protists are autotrophs, producing their food by photosynthesis. Photosynthetic protists belong to an informal category called **algae** (singular, *alga*). Algae may be unicellular, colonial, or multicellular, such as the one shown in **Figure 15.20a**. Other protists are heterotrophs, acquiring their food from other organisms. Some heterotrophic protists eat bacteria or other protists; some are fungus-like and obtain organic molecules by absorption. Still others are parasitic. A **parasite** derives its nutrition from a living host, which is harmed by the interaction. For example, the parasitic trypanosomes shown among human red blood cells in **Figure 15.20b** cause sleeping sickness, a debilitating disease common in parts of Africa. Yet other protists are mixotrophs, capable of both photosynthesis and heterotrophy. *Euglena* **(Figure 15.20c)**, a common inhabitant of pond water, can change its mode of nutrition, depending on availability of light and nutrients.

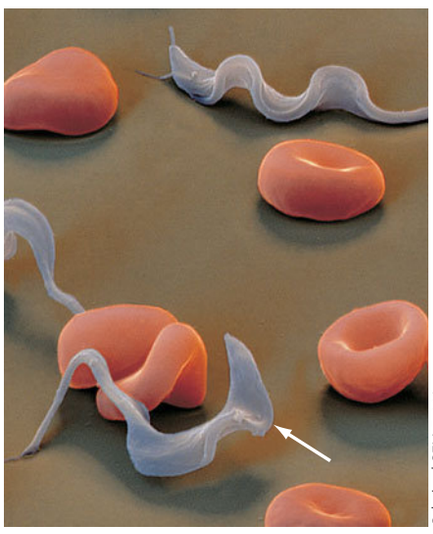
What do all protists have in common?

Protist habitats are also diverse. Most protists are aquatic, living in oceans, lakes, and ponds **(Figure 15.21)**. They are found almost anywhere there is moisture, including terrestrial habitats such as damp soil and leaf litter. Others reside in the bodies of various host organisms in mutually beneficial relationships. For example, coral reefs are made possible by the unicellular algae that inhabit the bodies of reef-building coral animals.

▼ Figure 15.20 Protist modes of nutrition.



(a) An autotroph: *Caulerpa*, a multicellular alga



Colorized SEM 5,440

(b) A heterotroph: parasitic trypanosome



LM 700

(c) A mixotroph: *Euglena*

And without the protists that inhabit their intestinal tract, termites would not be able to damage houses: Termite endosymbionts digest the tough cellulose in the wood.

Because the classification of protists remains a work in progress, our brief survey of protists is not organized to correspond with any hypothesis about phylogeny. Instead, we'll look at four major categories of protists, grouped by lifestyle: protozoans, slime molds, unicellular and colonial algae, and seaweeds.

Protozoans

Protists that live primarily by ingesting food are called **protozoans** (Figure 15.22). Protozoans thrive in all types of aquatic environments. Most species eat bacteria or other protozoans, but some can absorb nutrients dissolved in the water. Protozoans that live as parasites in animals, though in the minority, cause some of the world's most harmful diseases.

Flagellates are protozoans that move by means of one or more flagella. Most species are free-living (nonparasitic). However, this group also includes some nasty parasites that make people sick. An example is *Giardia*, a common waterborne parasite that causes severe diarrhea. People most often pick up *Giardia* by drinking water contaminated with feces containing the parasite. For example, a swimmer in a lake or river might accidentally ingest water, or a hiker might drink contaminated water from a seemingly pristine stream. (Boiling the water first will kill *Giardia*.) Another flagellate is *Trichomonas*, a common sexually transmitted parasite. The parasite travels through the reproductive tract by moving its flagella and undulating part of its membrane. In women, these protozoans feed on white blood cells and bacteria living on the cells lining the vagina. *Trichomonas* also infects the cells lining the male reproductive tract, but limited availability of food results in very small population sizes. Consequently, males typically have no symptoms of infection.

Amoebas are characterized by great flexibility in their body shape and the absence of permanent organelles for locomotion. Most species move and feed by means of **pseudopodia** (singular, *pseudopodium*), temporary extensions of the cell. Amoebas can assume virtually any shape as they creep over rocks, sticks, or mud at the bottom of a pond or ocean. One species of parasitic amoeba causes amoebic dysentery, a disease that is responsible for an estimated 100,000 deaths worldwide every year. Other protozoans with pseudopodia include the **forams**, which have shells. The pseudopodia extend through small pores in the shell. Although they are single-celled, the largest forams grow to a diameter of several centimeters. Ninety percent of forams that have been identified are fossils.

Apicomplexans are all parasitic, and some cause serious human diseases. They are named for a structure at their apex (tip) that is specialized for penetrating host cells and tissues. This group of protozoans includes *Plasmodium*, the parasite that causes malaria (see the Biology and Society essay in Chapter 13). Another apicomplexan is *Toxoplasma*. Millions of people in the United States carry *Toxoplasma* in their intestinal tracts but don't become sick because the immune system keeps the parasite in check. However, a woman who is newly infected with *Toxoplasma* during pregnancy can pass the parasite to her unborn child, who may suffer damage to the nervous system as a result. *Toxoplasma* can also cause serious disease in individuals whose immune systems are impaired, such as AIDS patients.

Ciliates are protozoans named for their hair-like structures called cilia, which provide movement for the protist and sweep food into its mouth. Nearly all ciliates are free-living (nonparasitic) and include both heterotrophs and mixotrophs. If you have had the opportunity to explore protist diversity in a droplet of pond water, you may have seen the common freshwater ciliate *Paramecium*. ☑

☑ CHECKPOINT

What three modes of locomotion occur among protozoans?

Answer: movement using flagella, cilia, and pseudopodia

▼ Figure 15.22 A diversity of protozoans.



Colorized SEM 2,400

A flagellate: *Giardia*. This flagellated protozoan parasite can colonize and reproduce within the human intestine, causing disease.



Colorized SEM 3,200

Another flagellate: *Trichomonas*. This common sexually transmitted parasite causes an estimated 5 million new infections each year.



Colorized TEM 2,300

An amoeba. This amoeba is beginning to wrap pseudopodia around an algal cell in preparation for engulfing it.

Slime Molds

These protists are more attractive than their name implies. Slime molds resemble fungi in appearance and lifestyle, but the similarities are due to convergent evolution; slime molds are more closely related to amoebas than to fungi. The weblike body of a slime mold, like that of a fungus, is an adaptation that increases exposure to the environment. This suits the role of these organisms as decomposers. The two main groups of these protists are plasmodial slime molds and cellular slime molds.

Plasmodial slime molds are named for the feeding stage in their life cycle, an amoeboid mass called a plasmodium **(Figure 15.23)**—not to be confused with *Plasmodium*, the apicomplexan parasite that causes malaria. You can find plasmodial slime molds among the leaf litter and other decaying material on a forest floor, and you won't need a microscope to see them. A plasmodium can measure several centimeters across, with its network of fine filaments taking in bacteria and bits of dead organic matter amoeboid style. Large as it is, the plasmodium is actually a single cell with many nuclei.

The study of **cellular slime molds** raises a question about what it means to be an individual organism, given the different forms they can take during their successive life stages **(Figure 15.24)**. The feeding stage of a cellular slime mold consists of 1 solitary amoeboid cells. They function individually, using their pseudopodia to creep through organic matter and engulf bacteria. But when food is in short supply, the amoeboid cells swarm together to form 2 a slug-like colony that moves and functions as a single unit. After a brief period of mobility, the colony 3 extends a stalk and develops into a multicellular reproductive structure. ✓

✓ CHECKPOINT

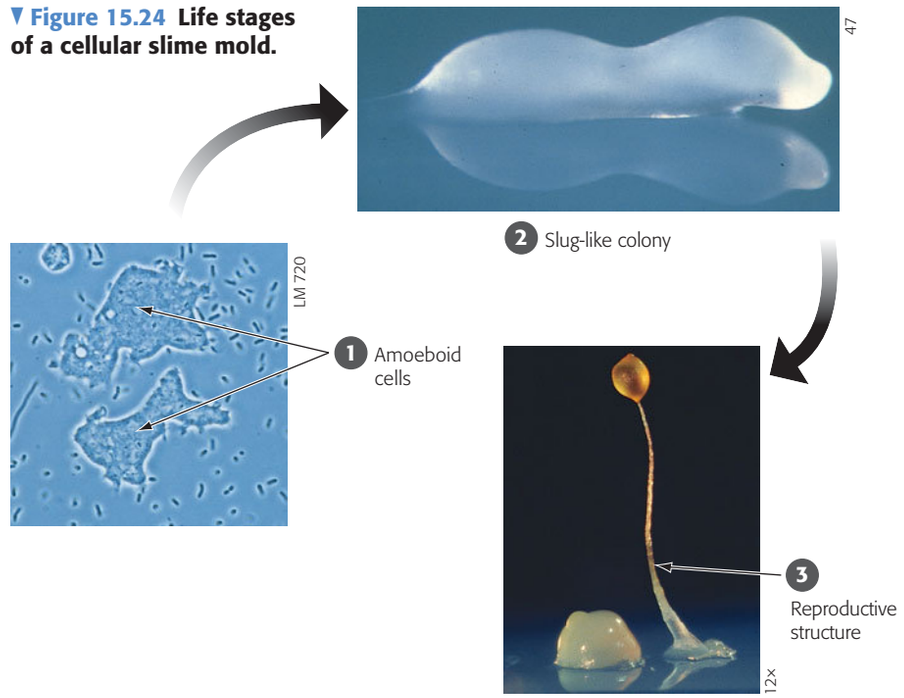
Which protozoans are most similar in their movement to the unicellular stage of slime molds?

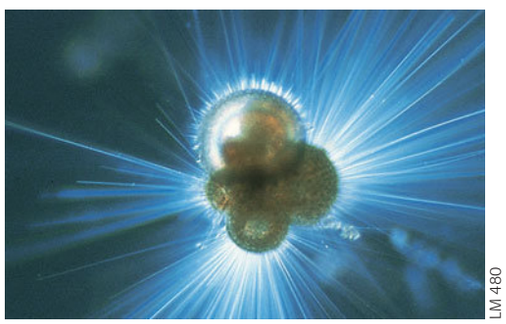
Answer: amoebas

Figure 15.23 A plasmodial slime mold. The weblike form of the slime mold's feeding stage is an adaptation that enlarges the organism's surface area, increasing its contact with food, water, and oxygen.

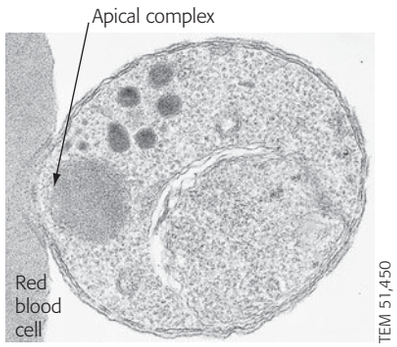


Figure 15.24 Life stages of a cellular slime mold.

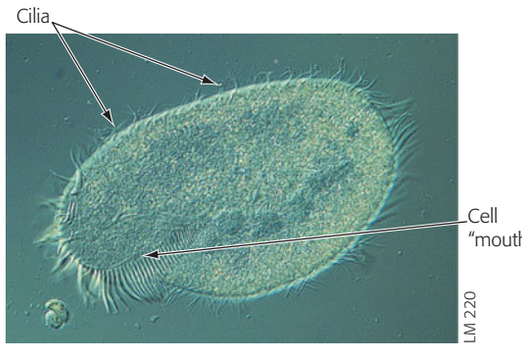




A foram. A foram cell secretes a shell made of organic material hardened with calcium carbonate. The shells of fossilized forams are a major component of limestone.



An apicomplexan. *Plasmodium*, which causes malaria, enters red blood cells of its human host. The parasite feeds on the host cell from within, eventually destroying it.



A ciliate. The ciliate *Paramecium* uses its cilia to move through pond water. Cilia lining the oral groove keep a current of water containing food moving toward the cell "mouth."

Unicellular and Colonial Algae

Algae are photosynthetic protists whose chloroplasts support food chains in freshwater and marine ecosystems. Researchers are currently trying to harness their ability to convert light energy to chemical energy for another purpose—to produce biofuels. We'll look at three groups of unicellular algae—dinoflagellates, diatoms, and green algae—and one type of colonial algae.

Many unicellular algae are components of **plankton**, the communities of organisms, mostly microscopic, that drift or swim weakly near the surfaces of ponds, lakes, and oceans. Dinoflagellates are abundant in the vast aquatic pastures of plankton. Each **dinoflagellate** species has a characteristic shape reinforced by external plates made of cellulose **(Figure 15.25a)**. The beating of two flagella in perpendicular grooves produces a spinning movement. Dinoflagellate blooms—population explosions—sometimes cause warm coastal waters to turn pinkish orange, a phenomenon known as a red tide. Toxins produced by some red-tide dinoflagellates have caused massive fish kills, especially in the tropics, and are poisonous to humans as well.

Diatoms have glassy cell walls containing silica, the mineral used to make glass **(Figure 15.25b)**. The cell wall consists of two halves that fit together like the bottom and lid of a shoe box. Diatoms store their food reserves in the form of an oil that provides buoyancy, keeping diatoms floating as plankton near the sunlit surface. Massive accumulations of fossilized diatoms make up thick sediments known as diatomaceous earth, which is mined for its use as a filtering material, an abrasive, and a natural insecticide.

Green algae are named for their grass-green chloroplasts. Unicellular green algae flourish in most freshwater lakes and ponds, as well as many home pools and aquariums. Some species are flagellated, such as *Chlamydomonas* **(Figure 15.25c)**. The green algal group also includes colonial forms, such as *Volvox*, shown in **Figure 15.25d**. Each *Volvox* colony is a hollow ball of flagellated cells (the small green dots in the photo) that are very similar to certain unicellular green algae. The balls within the balls in Figure 15.25d are daughter colonies that will be released when the parent colonies rupture. Of all photosynthetic protists, green algae are the most closely related to plants. (We'll examine the evidence of this evolutionary relationship in the next chapter.)

☑ CHECKPOINT

1. What metabolic process mainly distinguishes algae from protozoans?
2. Are seaweeds plants?

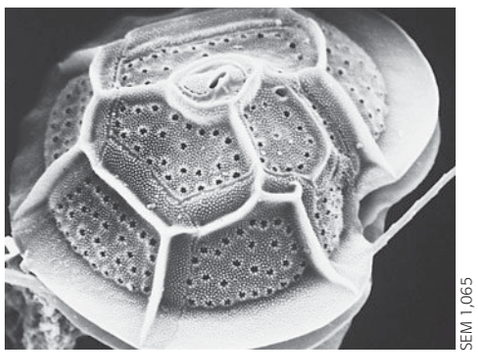
Answers: **1.** *photosynthesis* **2.** *No, they are large, multicellular marine algae.*

Seaweeds

Defined as large, multicellular marine algae, **seaweeds** grow on rocky shores and just offshore beyond the zone of the pounding surf. Their cell walls have slimy and rubbery substances that cushion their bodies against the agitation of the waves. Some seaweeds are as large and complex as many plants. And though the word *seaweed* implies a plantlike appearance, the similarities between these algae and plants are a consequence of convergent evolution. In fact, the closest relatives of seaweeds are certain unicellular algae, which is why many biologists include seaweeds with the protists. Seaweeds are classified into three different groups **(Figure 15.26)**, based partly on the types of pigments present in their chloroplasts: green algae, red algae, and brown algae (some of which are known as kelp).

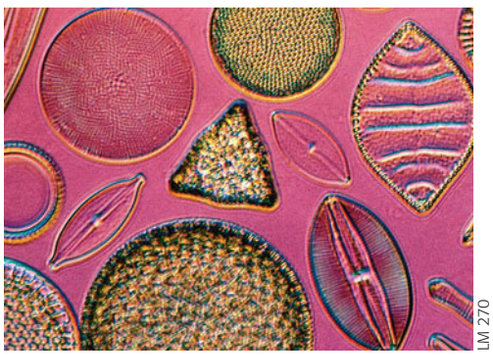
Many coastal people, particularly in Asia, harvest seaweeds for food. For example, in Japan and Korea, some seaweed species, including brown algae called kombu, are ingredients in soups. Other seaweeds, such as red algae called nori, are used to wrap sushi. Marine algae are rich in iodine and other essential minerals. However, much of their organic material consists of unusual polysaccharides that humans cannot digest, which prevents seaweeds from becoming staple foods. They are eaten mostly for their rich tastes and unusual textures. The gel-forming substances in the cell walls of seaweeds are widely used as thickeners for such processed foods as puddings, ice cream, and salad dressing. The seaweed extract called agar provides the gel-forming base for the media microbiologists use to culture bacteria in petri dishes and for a type of gel commonly used to perform gel electrophoresis (as shown in Figure 12.17). ☑

▼ Figure 15.25 Unicellular and colonial algae.



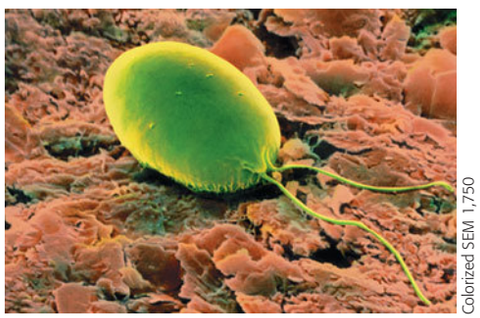
SEM 1,065

(a) A dinoflagellate, with its wall of protective plates



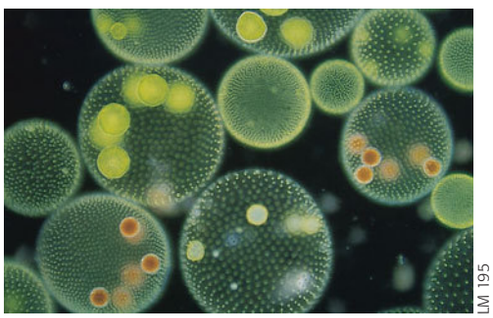
LM 270

(b) A sample of diverse diatoms, which have glassy walls



Colorized SEM 1,750

(c) *Chlamydomonas*, a unicellular green alga with a pair of flagella



LM 195

(d) *Volvox*, a colonial green alga

Figure 15.26 The three major groups of seaweeds.



Green algae. This sea lettuce is an edible species that inhabits the intertidal zone, where the land meets the ocean. In addition to seaweeds, green algae include unicellular and colonial species.



Red algae. These seaweeds are most abundant in the warm coastal waters of the tropics. Because their chloroplasts have special pigments that absorb the blue and green light that penetrates best through water, red algae can generally live in the deepest water.



Brown algae. This group includes the largest seaweeds, known as kelp, which grow as marine "forests" in relatively deep water beyond the intertidal zone.



How Life Began EVOLUTION CONNECTION

The Origin of Multicellular Life

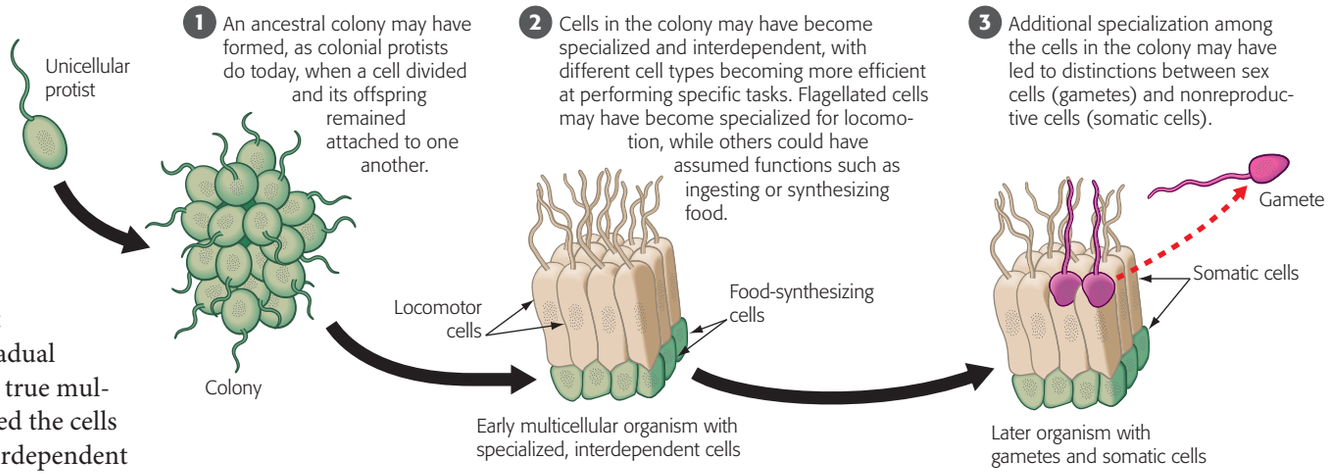
An orchestra can play a greater variety of musical compositions than a violin soloist can. Put simply, increased complexity makes more variations possible. Thus, the origin of the eukaryotic cell led to an evolutionary radiation of new forms of life. Unicellular protists, which are organized on the complex eukaryotic plan, are much more diverse in form than the simpler prokaryotes. The evolution of multicellular bodies crossed another threshold in structural organization.

Multicellular organisms are fundamentally different from unicellular ones. In a unicellular organism, all of life's activities are carried out by a single cell. In contrast, a multicellular organism has various specialized cells that perform different functions—such as feeding, waste disposal, gas exchange, and protection—and are dependent on each other.

The evolutionary links between unicellular and multicellular life were probably colonial forms, in which unicellular protists stuck together as loose federations of independent cells **(Figure 15.27)**. The gradual transition from colonies to true multicellular organisms involved the cells becoming increasingly interdependent as a division of labor evolved. We can see one level of specialization and cooperation in the colonial green alga *Volvox* (see Figure 15.25d). *Volvox* produces gametes (sperm and ova), which depend on nonreproductive (somatic) cells while developing. Cells in truly multicellular organisms are specialized for many more nonreproductive functions.

Multicellularity evolved many times among the ancestral stock of protists, leading to new waves of biological diversification. The diverse seaweeds are examples of their descendants, and so are plants, fungi, and animals. In the next chapter, we'll trace the long evolutionary movement of plants and fungi onto land.

Figure 15.27 A model for the evolution of multicellular organisms from unicellular protists.



Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Major Episodes in the History of Life

Major episode	Millions of years ago
Plants and fungi colonize land	500
All major animal phyla established	530
First multicellular organisms	1,200
Oldest eukaryotic fossils	1,800
Accumulation of O_2 in atmosphere	2,400
Oldest prokaryotic fossils	3,500
Origin of Earth	4,600

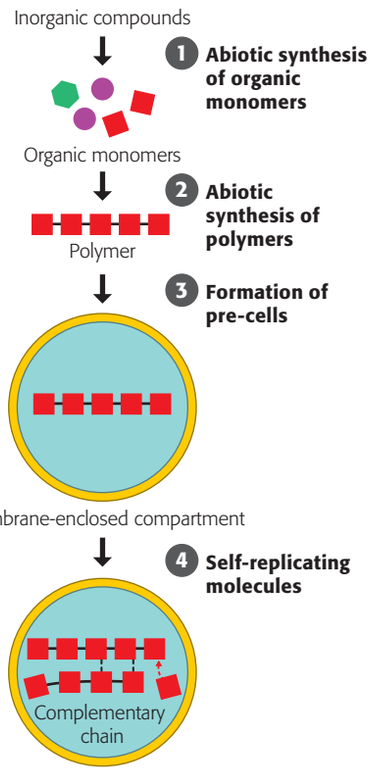
The Origin of Life

Resolving the Biogenesis Paradox

All life today arises only by the reproduction of preexisting life. However, most biologists think it is possible that chemical and physical processes in Earth's primordial environment produced the first cells through a series of stages.

A Four-Stage Hypothesis for the Origin of Life

One scenario suggests that the first organisms were products of chemical evolution in four stages:



From Chemical Evolution to Darwinian Evolution

Over millions of years, natural selection favored the most efficient pre-cells, which evolved into the first prokaryotic cells.

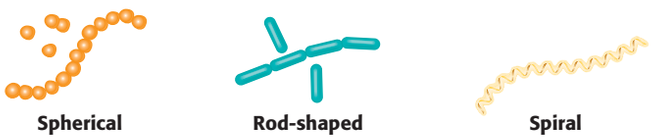
Prokaryotes

They're Everywhere!

Prokaryotes are found wherever there is life and greatly outnumber eukaryotes. Prokaryotes thrive in habitats where eukaryotes cannot live. A few prokaryotic species cause serious disease, but most are either benign or beneficial to other forms of life.

The Structure and Function of Prokaryotes

Prokaryotic cells lack nuclei and other membrane-enclosed organelles. Most have cell walls. Prokaryotes exhibit three common shapes.

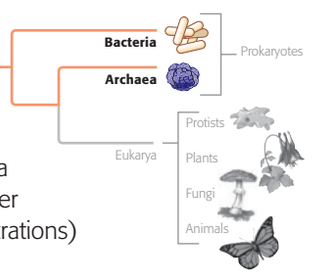


About half of all prokaryotic species are mobile, most of these using flagella to move. Some prokaryotes can survive extended periods of harsh conditions by forming endospores. Many prokaryotes can reproduce by binary fission at high rates if conditions are favorable, but growth is usually restricted by limited resources.

Prokaryotes exhibit all four major modes of nutrition.

Nutritional Mode	Energy Source	Carbon Source
Photoautotroph	Sunlight	CO_2
Chemoautotroph	Inorganic chemicals	
Photoheterotroph	Sunlight	Organic compounds
Chemoheterotroph	Organic compounds	

The Two Main Branches of Prokaryotic Evolution: Bacteria and Archaea



The prokaryotic lineage includes domains Bacteria and Archaea. Many archaea are "extremophiles" capable of surviving under conditions (such as high heat or salt concentrations) that would kill other forms of life.

Bacteria and Disease

Most pathogenic bacteria cause disease by producing exotoxins or endotoxins. Sanitation, antibiotics, and education are the best defenses against bacterial disease. Several bacteria have the potential to be formidable weapons.

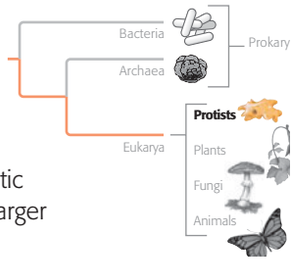
The Ecological Impact of Prokaryotes

Prokaryotes help recycle chemical elements between the biological and physical components of ecosystems. People use prokaryotes to remove pollutants from water, air, and soil in the process called bioremediation.

Protists

The Origin of Eukaryotic Cells

The nucleus and endomembrane system of eukaryotes probably evolved from infoldings of the plasma membrane of ancestral prokaryotes. Mitochondria and chloroplasts probably evolved from symbiotic prokaryotes that took up residence inside larger cells, a process called endosymbiosis.



The Diversity of Protists

Protists are unicellular eukaryotes and their closest multicellular relatives.

- Protozoans (including flagellates, amoebas, apicomplexans, and ciliates) primarily live in aquatic environments and ingest their food.
- Slime molds (including plasmodial slime molds and cellular slime molds) resemble fungi in appearance and lifestyle as decomposers, but are not at all closely related.
- Unicellular algae (including dinoflagellates, diatoms, and unicellular green algae) are photosynthetic protists that support food chains in freshwater and marine ecosystems.
- Seaweeds—which include green, red, and brown algae—are large, multicellular marine algae that grow on and near rocky shores.

SELF-QUIZ

1. Place these events in the history of life on Earth in the order that they occurred.
   a. colonization of land by animals
   b. colonization of land by plants and fungi
   c. diversification of animals (Cambrian explosion)
   d. origin of eukaryotes
   e. origin of humans
   f. origin of multicellular organisms
   g. origin of prokaryotes
2. Place the following steps in the origin of life in the order that they are hypothesized to have occurred.
   a. integration of abiotically produced molecules into membrane-enclosed pre-cells
   b. origin of the first molecules capable of self-replication
   c. abiotic joining of organic monomers into polymers
   d. abiotic synthesis of organic monomers
   e. natural selection among pre-cells
3. DNA replication relies on the enzyme DNA polymerase. Why does this suggest that the earliest genes were made from RNA?
4. Contrast exotoxins with endotoxins.
5. What is the difference between autotrophs and heterotrophs in terms of the source of their organic compounds?
6. The bacteria that cause tetanus can be killed only by prolonged heating at temperatures considerably above boiling. What does this suggest about tetanus bacteria?
7. To what nutritional classification do you belong? To what nutritional classification does a mushroom belong? (*Hint:* Review Figure 15.12.)
8. Why are protists especially important to biologists investigating the evolution of eukaryotic life?
9. Of the following, which describes protists most inclusively?
   a. multicellular eukaryotes
   b. protozoans
   c. eukaryotes that are not plants, fungi, or animals
   d. single-celled organisms closely related to bacteria
10. Which algal group is most closely related to plants?
    a. diatoms
    b. green algae
    c. dinoflagellates
    d. seaweeds

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

11. Imagine you are on a team designing a moon base that will be self-contained and self-sustaining. Once supplied with building materials, equipment, and organisms from Earth, the base will be expected to function indefinitely. One of the members of your team has suggested that everything sent to the base be chemically treated or irradiated so that no bacteria of any kind are present. Do you think this is a good idea? Predict some of the consequences of eliminating all bacteria from an environment.
12. Your classmate says that organisms that require oxygen existed before photosynthetic organisms. Do you support this idea? Explain why or why not.

BIOLOGY AND SOCIETY

13. Many local newspapers publish a weekly list of restaurants that have been cited by inspectors for poor sanitation. Locate such a report and highlight the cases that are probably associated with food contamination by pathogenic prokaryotes.
14. What do you think should be done to prevent attacks by terrorists using biological weapons?

16 Plants, Fungi, and the Move onto Land



A white truffle being offered for auction. Alba, Italy, a region renowned for producing rare white truffles, holds an annual auction that attracts restauranteurs and gourmets from all over the world.



CHAPTER CONTENTS

Colonizing Land 316
Plant Diversity 318
Fungi 328

CHAPTER THREAD
Plant-Fungus Symbiosis

BIOLOGY AND SOCIETY
The Diamond of the Kitchen 315
THE PROCESS OF SCIENCE
Did a Fungus Lead to the Salem Witch Hunt? 331
EVOLUTION CONNECTION
Mutually Beneficial Symbiosis 332



Plant-Fungus Symbiosis BIOLOGY AND SOCIETY

The Diamond of the Kitchen

To the untrained eye, a truffle (the fungus, not the chocolate) is an unappealing lump that you probably wouldn't eat on a dare. But despite their unappetizing appearance, truffles are treasured by gourmets as "diamonds of the kitchen." They command prices up to hundreds of dollars per ounce for the best specimens. A 3.3-pound white truffle—an unusually large individual of the rarest variety—brought a record $330,000 at auction. What's the attraction? Rather than their taste, truffles are prized for their powerful scent, which has been described as earthy or moldy. A little truffle goes a long way. Chefs only need to add a few shavings from a truffle to infuse a dish with its delectable essence.

Truffles are the subterranean reproductive bodies of certain fungi. Their job is to produce spores, single cells that are capable of growing into a new fungus, just as a seed can grow into a new plant. It is generally advantageous for seeds or spores to start their lives in a new place, away from the ground inhabited by their parents. And that's where the potent truffle smell comes in. Attracted by the heady aroma, animals excavate and eat the fungi and later deposit the hardy spores in their feces. Human noses are not sensitive enough to locate the buried treasures, so truffle hunters use pigs or trained dogs to sniff out their quarry.

Besides being culinary gems, truffles represent the essential role of fungi as the hidden power behind the throne of the plant kingdom. The roots of most plants are surrounded—in some cases even permeated—by a finely woven web of fungal filaments. Truffles, for example, have such a relationship with certain species of trees. This association is an example of **symbiosis**, an interaction in which one species lives in or on another species. The ultrathin filaments reach into pockets between the soil grains that are too small for roots to enter, absorbing water and inorganic nutrients and passing them to the plant. The plant returns the favor by supplying the fungus with sugars and other organic molecules. This relationship between fungus and root is evident on some of the oldest plant fossils, suggesting that the mutually beneficial symbiosis was crucial to the colonization of land.

Colonizing Land

Plants are terrestrial (land-dwelling) organisms. It is true that some, such as water lilies, have returned to the water, but they evolved from terrestrial ancestors (just as several species of aquatic mammals, such as whales, evolved from terrestrial mammals). In this section, we'll discuss some of the adaptations that allowed plants to move onto land.

Terrestrial Adaptations of Plants

Why aren't seaweeds considered plants?

What exactly is a plant? A **plant** is a multicellular eukaryote that makes organic molecules by photosynthesis; that is, they are photoautotrophs (see Figure 15.12). Photosynthesis distinguishes plants from the animal and fungal kingdoms. But what about large algae, including seaweeds, which we classified as protists in the preceding chapter? They, too, are multicellular, eukaryotic, and photosynthetic. What distinguishes plants from algae is a set of structural and reproductive terrestrial adaptations.

Structural Adaptations

Living on land poses different problems than living in water **(Figure 16.1)**. In terrestrial habitats, the resources that a photosynthetic organism needs are found in two very different places. Light and carbon dioxide are mainly available in the air, while water and mineral nutrients are found mainly in the soil. Thus, the complex bodies of plants are specialized to take advantage of these two environments by having both aerial leaf-bearing organs called **shoots** and subterranean organs called **roots**.

As you learned in the Biology and Society section, most plants have symbiotic fungi associated with their roots. These root-fungus combinations are called **mycorrhizae** ("fungus roots") **(Figure 16.2)**. For their part, the fungi absorb water and essential minerals from the soil and provide these materials to the plant. The sugars produced by the plant nourish the fungi. Mycorrhizae are key adaptations that made it possible for plants to live on land.

Shoots also show structural adaptations to the terrestrial environment. Leaves are the main photosynthetic organs of most plants. Exchange of carbon dioxide (CO_2) and oxygen (O_2) between the atmosphere and the

Figure 16.1 Structural adaptations of algae and plants.

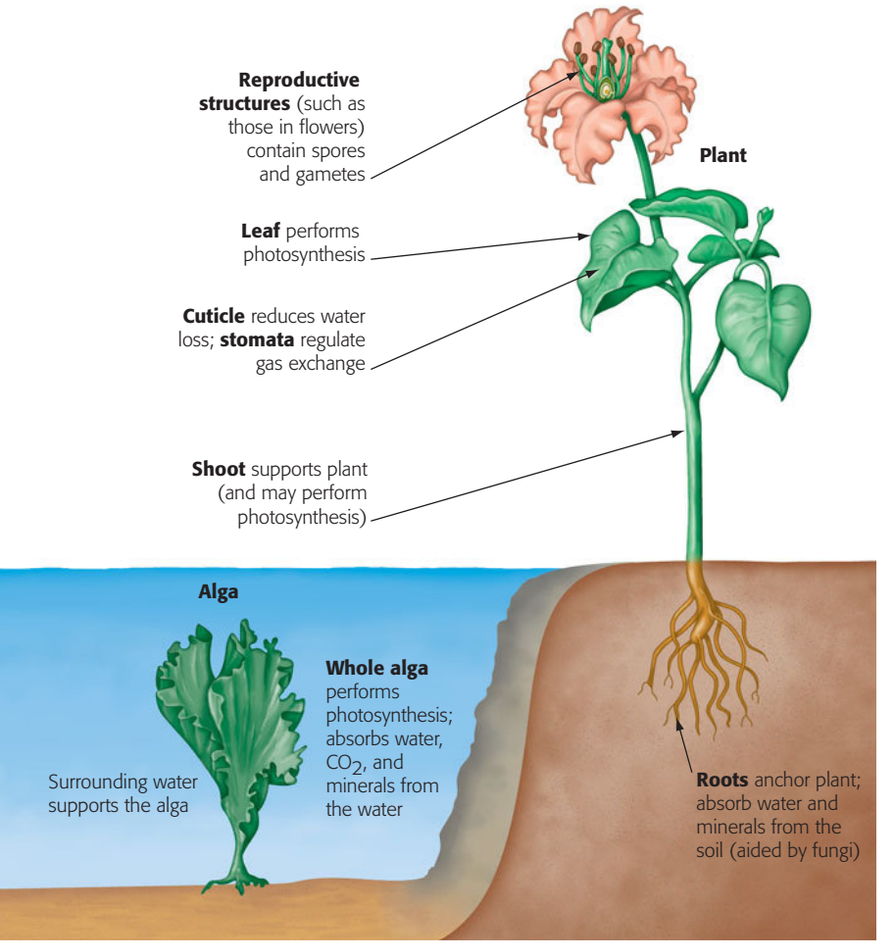
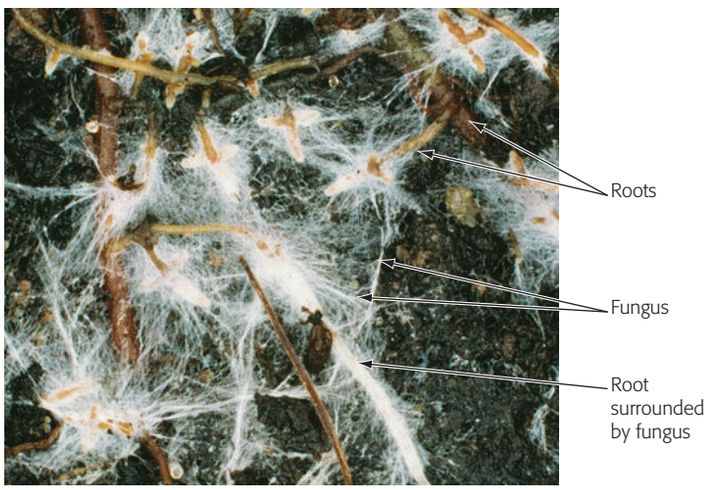


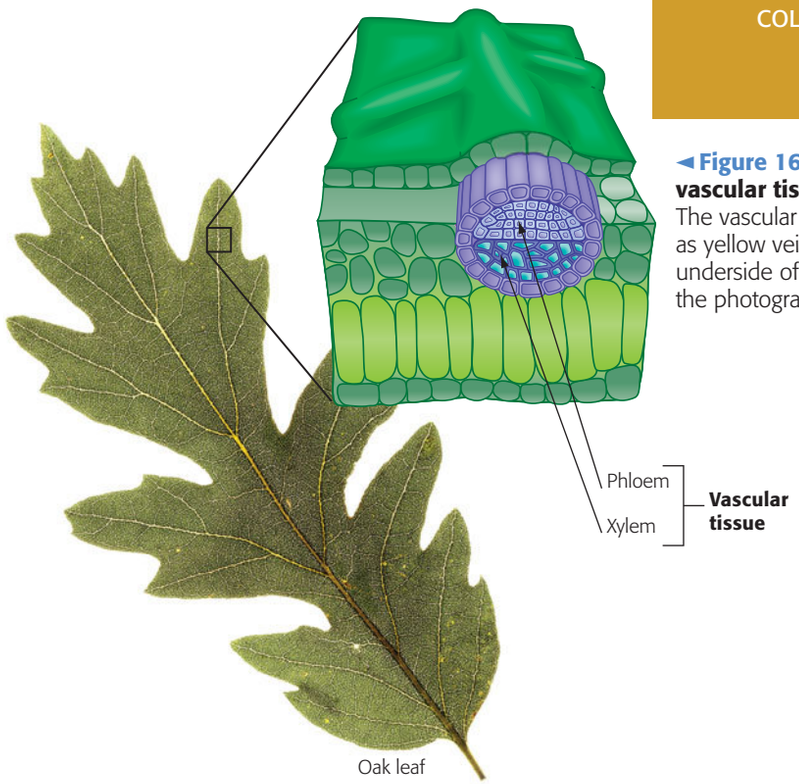
Figure 16.2 Mycorrhizae: symbiotic associations of fungi and roots. The finely branched filaments of the fungus (white in the photo) provide an extensive surface area for absorption of water and minerals from the soil.



photosynthetic interior of a leaf occurs via **stomata** (singular, *stoma*), the microscopic pores found on a leaf's surface (see Figure 7.2). A waxy layer called the **cuticle** coats the leaves and other aerial parts of most plants, helping the plant body retain water (see Figure 18.8b).

Differentiation of the plant body into shoot and root systems solved one problem but created new ones. For the shoot system to stand up straight in the air, it must have support. This is not a major problem in the water: Huge seaweeds do not need skeletons because the surrounding water buoys them. An important terrestrial adaptation of plants is **lignin**, a chemical that hardens cell walls. Imagine what would happen to you if your skeleton were to suddenly turn mushy. A tree would also collapse if it were not for its "skeleton," its framework of lignin-rich cell walls.

Specialization of the plant body into shoots and roots also introduced the problem of transporting vital materials between the distant organs. The terrestrial equipment of most plants includes **vascular tissue**, a system of tube-shaped cells that branch throughout the plant **(Figure 16.3)**. The vascular tissue actually has two types of tissues specialized for transport: **xylem**, consisting of dead cells with tubular cavities for transporting water and minerals from roots to leaves; and **phloem**, consisting of living cells that distribute sugars from the leaves to the roots and other nonphotosynthetic parts of the plant.



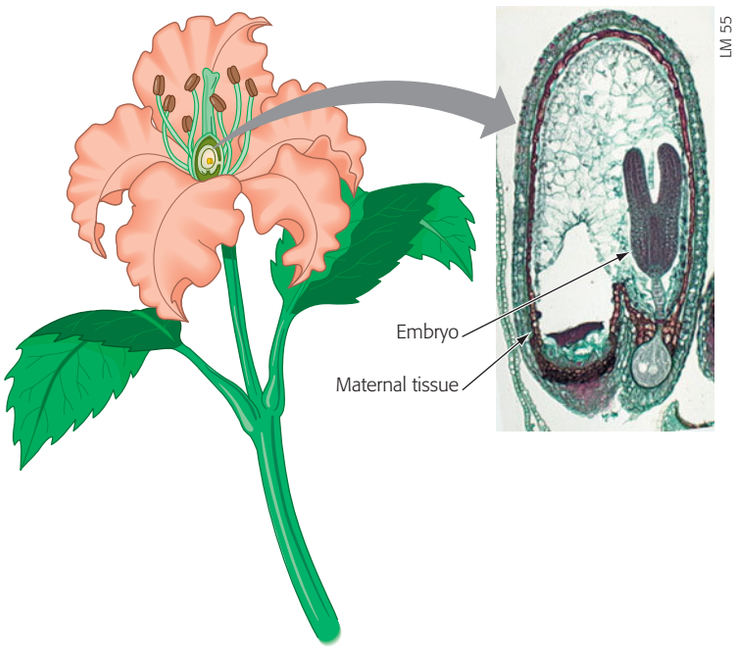
◄ Figure 16.3 Network of vascular tissue in a leaf. The vascular tissue is visible as yellow veins on the underside of the leaf in the photograph.

Reproductive Adaptations

Adapting to land also required a new mode of reproduction. For algae, the surrounding water ensures that gametes (sperm and eggs) and developing offspring stay moist. The aquatic environment also provides a means of dispersing the gametes and offspring. Plants, however, must keep their gametes and developing offspring from drying out in the air. Plants (and some algae) produce their gametes in protective structures that are called **gametangia** (singular, *gametangium*). A gametangium has a jacket of protective cells surrounding a moist chamber where gametes can develop without dehydrating.

For most plants, sperm reach the eggs by traveling inside pollen grains, which are carried by wind or animals. The egg remains within tissues of the mother plant and is fertilized there. In plants, but not algae, the zygote (fertilized egg) develops into an embryo while still contained within the female parent, which protects the embryo and keeps it from dehydrating **(Figure 16.4)**. Most plants rely on wind or animals, such as fruit-eating birds or mammals, to disperse their offspring, which are in the form of embryos contained in seeds. ☑

▼ Figure 16.4 The protected embryo of a plant. Internal fertilization, with sperm and egg combining within a moist chamber on the mother plant, is an adaptation for living on land. The female parent continues to nurture and protect the plant embryo, which develops from the zygote.



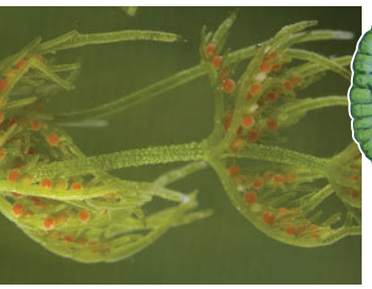
☑ CHECKPOINT

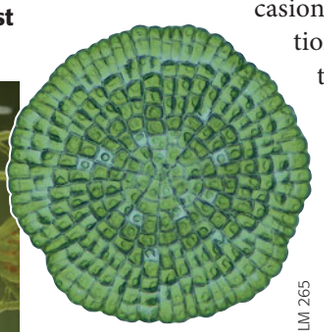
Name some adaptations of plants for living on land.

Answer: any of the following: cuticle; stomata; vascular tissue; lignin-hardened cell walls; gametangia, which protect gametes; protected embryos; and differentiation of the body into aerial shoots and subterranean roots

The Origin of Plants from Green Algae

Figure 16.5 Two species of charophytes, the closest algal relatives of plants.





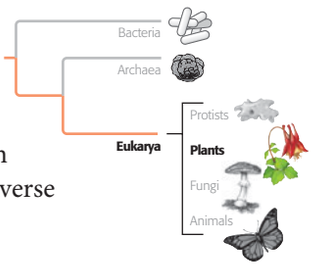
LM 265

The algal ancestors of plants carpeted moist fringes of lakes or coastal salt marshes over 500 million years ago. These shallow-water habitats were subject to occasional drying, and natural selection would have favored algae that could survive periodic droughts. Some species accumulated adaptations that enabled them to live permanently above the water line. A modern-day lineage of green algae, the **charophytes** (Figure 16.5), may resemble one of these early plant ancestors. Plants and present-day charophytes probably evolved from a common ancestor.

Adaptations making life on dry land possible had accumulated by about 475 million years ago, the age of the oldest known plant fossils. The evolutionary novelties of these first land plants opened the new frontier of a terrestrial habitat. Early plant life would have thrived in the new environment. Bright sunlight was abundant on land, the atmosphere had a wealth of carbon dioxide, and at first there were relatively few pathogens and plant-eating animals. The stage was set for an explosive diversification of plant life.

Plant Diversity

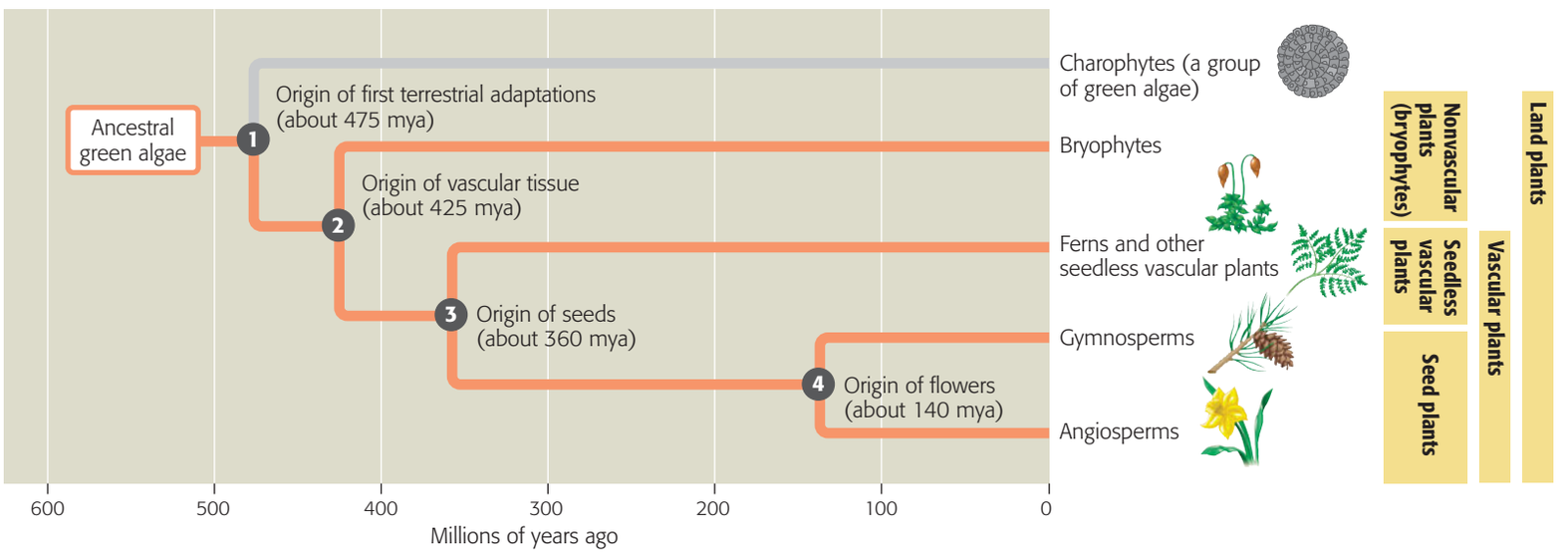
As we survey the diversity of modern plants, remember that the past is the key to the present. The history of the plant kingdom is a story of adaptation to diverse terrestrial habitats.



Highlights of Plant Evolution

The fossil record chronicles four major periods of plant evolution, which are also evident in the diversity of modern plants (Figure 16.6). Each stage is marked by the evolution of structures that opened new opportunities on land.

Figure 16.6 Highlights of plant evolution. This phylogenetic tree highlights the evolution of structures that allowed plants to move onto land; these structures still exist in modern plants. As we survey the diversity of plants, miniature versions of this tree will help you place each plant group in its evolutionary context.



1 After plants originated from an algal ancestor approximately 475 million years ago, early diversification gave rise to nonvascular plants, including mosses, liverworts, and hornworts. These plants, called **bryophytes**, lack true roots and leaves. Bryophytes also lack lignin, the wall-hardening material that enables other plants to stand tall. Without lignified cell walls, bryophytes have weak upright support. The most familiar bryophytes are **mosses**. A mat of moss actually consists of many plants growing in a tight pack, holding one another up. Gametangia, which protect the gametes and embryos, are a terrestrial adaptation that originated in bryophytes.

2 The second period of plant evolution, begun about 425 million years ago, was the diversification of

plants with vascular tissue. The presence of conducting tissues hardened with lignin allowed vascular plants to grow much taller, rising above the ground to achieve significant height. The earliest vascular plants lacked seeds. Today, this seedless condition is retained by **ferns** and a few other groups of vascular plants.

3 The third major period of plant evolution began with the origin of the seed about 360 million years ago. Seeds advanced the colonization of land by further protecting plant embryos from drying and other hazards. A **seed** consists of an embryo packaged along with a store of food within a protective covering. The seeds of early seed plants were not enclosed in any specialized chambers. These plants gave rise to the **gymnosperms** ("naked seeds"). Today, the most widespread and diverse gymnosperms are the **conifers**, consisting mainly of cone-bearing trees, such as pines.

4 The fourth major episode in the evolutionary history of plants was the emergence of flowering plants, or **angiosperms** ("contained seeds"), at least 140 million years ago. The **flower** is a complex reproductive structure that bears seeds within protective chambers called ovaries. This contrasts with the naked seeds of gymnosperms. The great majority of living plants—some 250,000 species—are angiosperms, including all our fruit and vegetable crops, grains and other grasses, and most trees.

With these highlights as our framework, we are now ready to survey the four major groups of modern plants: bryophytes, ferns, gymnosperms, and angiosperms (Figure 16.7). ☑

☑ CHECKPOINT

Name the four major groups of plants. Name an example of each.

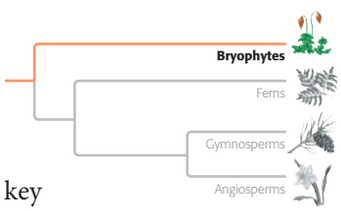
Answer: bryophytes (mosses), seedless vascular plants (ferns), gymnosperms (conifers), angiosperms (plants that produce fruits and vegetables)

▼ **Figure 16.7 The major groups of plants.**

PLANT DIVERSITY

Bryophytes (nonvascular plants)	**Ferns** (seedless vascular plants)	**Gymnosperms** (naked-seed plants)	**Angiosperms** (flowering plants)
			

Bryophytes



Mosses, which are bryophytes, may sprawl as low mats over acres of land (Figure 16.8). Mosses display two of the key terrestrial adaptations that made the move onto land possible: (1) a waxy cuticle that helps prevent dehydration and (2) the retention of developing embryos within the mother plant's gametangium. However, mosses are not totally liberated from their ancestral aquatic habitat. Mosses need water to reproduce because their sperm need to swim to reach eggs within the female gametangium. (A film of rainwater or dew is enough moisture for the sperm to travel.) In addition,

▼ **Figure 16.8 A peat moss bog in Scotland.** Mosses are bryophytes, which are nonvascular plants. Sphagnum mosses, collectively called peat moss, carpet at least 3% of Earth's land surface. They are most commonly found in high northern latitudes. The ability of peat moss to absorb and retain water makes it an excellent addition to garden soil.

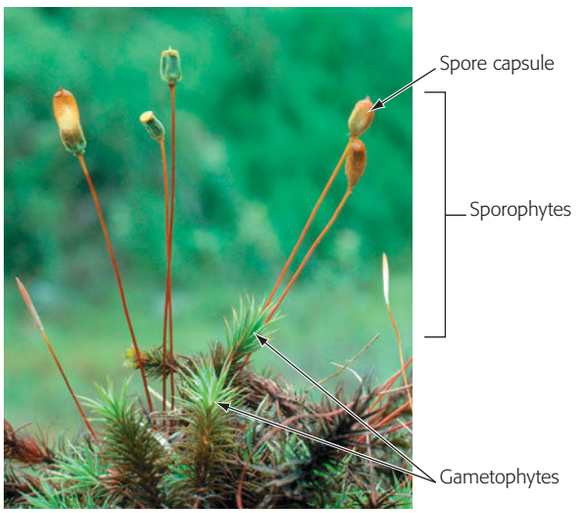


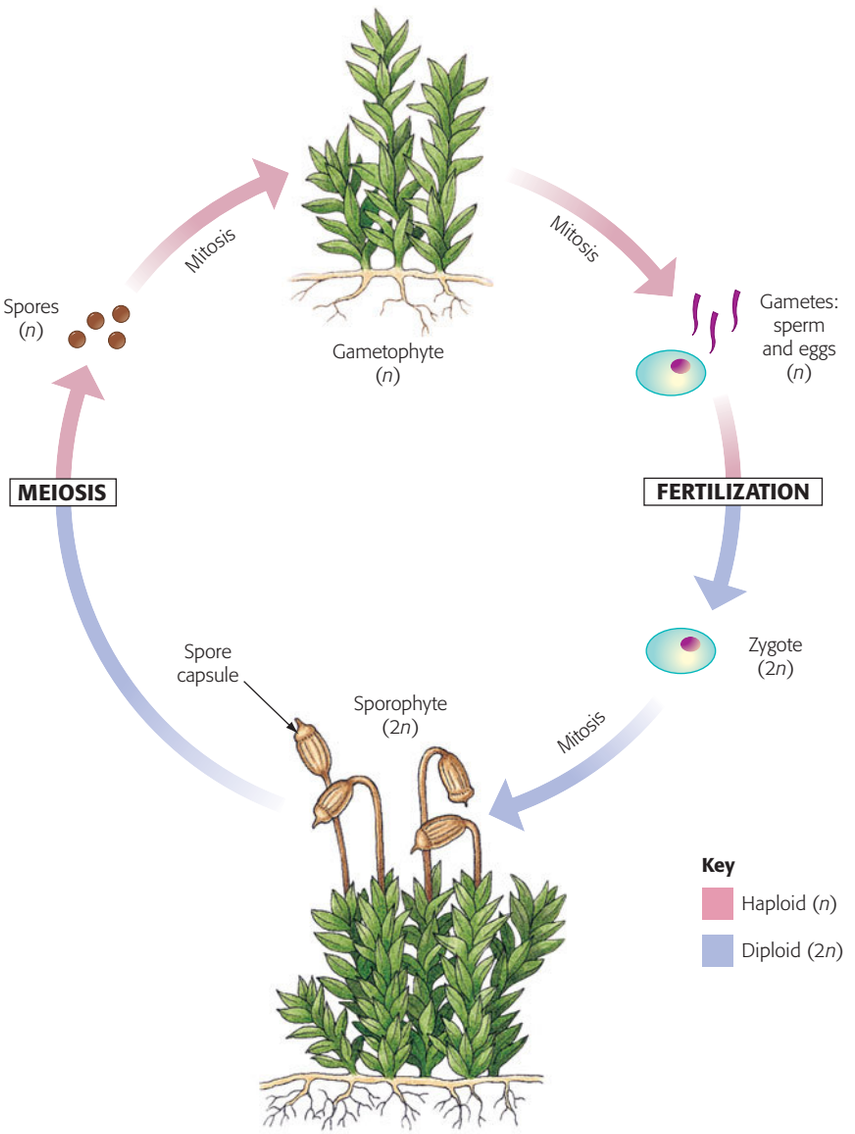
because most mosses have no vascular tissue to carry water from soil to aerial parts of the plant, they need to live in damp, shady places.

If you examine a mat of moss closely, you can see two distinct forms of the plant. The green, sponge-like plant that is the more obvious is called the **gametophyte**. Careful examination will reveal the other form of the moss, called a **sporophyte**, growing out of a gametophyte as a stalk with a capsule at its tip **(Figure 16.9)**. The cells of the gametophyte are haploid—they have one set of chromosomes (see Figure 8.12). In contrast, the sporophyte is made up of diploid cells (with two chromosome sets). These two different stages of the plant life cycle are named for the types of reproductive cells they produce. Gametophytes produce gametes (sperm and eggs), while sporophytes produce spores. A **spore** is a haploid cell that can develop into a new individual without fusing with another cell (two gametes must fuse to form a zygote). Spores usually have tough coats that enable them to survive in harsh environments. Seedless plants, including mosses and ferns, disperse their offspring as spores rather than as multicellular seeds.

The gametophyte and sporophyte are alternating generations that take turns producing each other. Gametophytes produce gametes that unite to form zygotes, which develop into new sporophytes. And sporophytes produce spores that give rise to new gametophytes. This type of life cycle, called **alternation of generations**, occurs only in plants and multicellular green algae **(Figure 16.10)**. Among plants, mosses and other bryophytes are unique in having the gametophyte as the larger, more obvious plant. As we continue our survey of plants, we'll see an increasing dominance of the sporophyte as the more highly developed generation. ☑

▼ Figure 16.9 The two forms of a moss. The feathery plant we generally know as a moss is the gametophyte. The stalk with the capsule at its tip is the sporophyte.





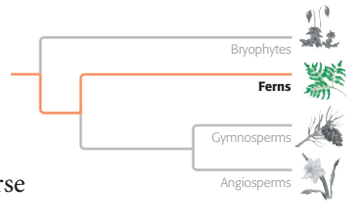
► Figure 16.10 Alternation of generations. Plants have life cycles very different from ours. Each of us is a diploid individual; the only haploid stages in the human life cycle, as for nearly all animals, are sperm and eggs. By contrast, plants have alternating generations: Diploid (2*n*) individuals (sporophytes) and haploid (*n*) individuals (gametophytes) generate each other in the life cycle.

☑ CHECKPOINT

Bryophytes, like all plants, have a life cycle that involves an alternation of generations. What are the two generations called? Which generation dominates in bryophytes?

Answer: gametophyte, sporophyte; gametophyte

Ferns



Ferns took terrestrial adaptation to the next level with the evolution of vascular tissue. Ferns are by far the most diverse seedless vascular plants, with more than 12,000 known species. However, the sperm of ferns, like those of mosses, have flagella and must swim through a film of water to fertilize eggs. Most ferns inhabit the tropics, although many species are found in temperate forests, such as many woodlands in the United States **(Figure 16.11)**.

During the Carboniferous period, from about 360 to 300 million years ago, ancient ferns were part of a much greater diversity of seedless plants that formed vast, swampy tropical forests over much of what is now Eurasia and North America **(Figure 16.12)**. As the plants died, they fell into stagnant wetlands and did not decay completely. Their remains formed thick organic deposits. Later, seawater flooded the swamps, marine sediments covered the organic deposits, and pressure and heat gradually converted them to coal. Coal is black sedimentary rock made up of fossilized plant material. Like coal, oil and natural gas also formed from the remains of long-dead organisms; thus, all three are known as **fossil fuels**. Since the Industrial Revolution, coal has been a crucial source of energy for people. However, burning these fossil fuels releases CO_2 and other greenhouse gases into the atmosphere, contributing to global climate change. ☑

▼ Figure 16.11 Ferns (seedless vascular plants). The ferns in the foreground are growing on the forest floor in Redwood National Park, California. The fern generation familiar to us is the sporophyte generation. You would have to crawl on the forest floor and explore with careful hands and sharp eyes to find fern gametophytes (upper right), tiny plants growing on or just below the soil surface.





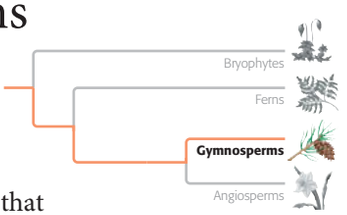
◄ Figure 16.12 A "coal forest" of the Carboniferous period. This painting, based on fossil evidence, reconstructs one of the great seedless forests. Most of the large trees belong to ancient groups of seedless vascular plants that are represented by just a few present-day species. The plants near the base of the trees are ferns.

☑ CHECKPOINT

Why are ferns able to grow taller than mosses?

Answer: Vascular tissue hardened with lignin allows ferns to stand taller and transport nutrients farther.

Gymnosperms



"Coal forests" dominated the North American and Eurasian landscapes until near the end of the Carboniferous period. At that time, the global climate turned drier and colder, and the vast swamps began to disappear. This climatic change provided an opportunity for seed plants, which can complete their life cycles on dry land and withstand long, harsh winters. Of the earliest seed plants, the most successful were the gymnosperms, and several kinds grew along with the seedless plants in the Carboniferous swamps. Their descendants include the conifers, or cone-bearing plants. Let's take a closer look at the conifers before discussing the adaptations that allowed seed plants to dominate the land.

What is the oldest tree in the United States?

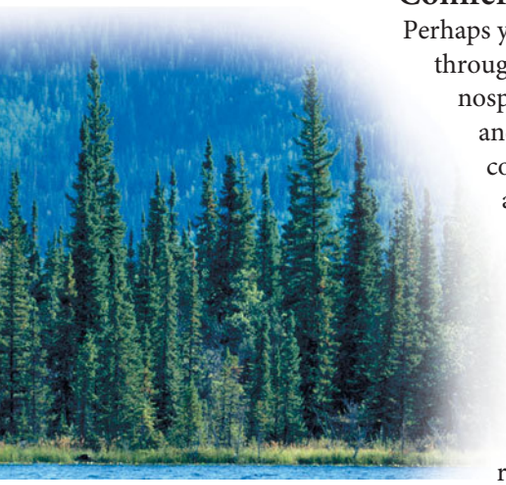
Conifers

Perhaps you have had the fun of hiking or skiing through a forest of conifers, the most common gymnosperms. Pines, firs, spruces, junipers, cedars, and redwoods are all conifers. A broad band of coniferous forests covers much of northern Eurasia and North America and extends southward in mountainous regions **(Figure 16.13)**. Today, about 190 million acres of coniferous forests in the United States, mostly in the western states and Alaska, are designated national forests.

Conifers are among the tallest, largest, and oldest organisms on Earth. Coastal redwoods, native to the northern California coast, are the world's tallest trees—up to 110 m, the height of a 33-story building. Giant sequoias, relatives of redwoods that grow in the Sierra Nevada mountains of California, are massive. One, known as the General Sherman tree, is about 84 m (275 feet) high and outweighs the combined weight of a dozen space shuttles. Bristlecone pines, another species of California conifer, are among the oldest organisms alive. One bristlecone pine is more than 4,600 years old; it was a young tree when people invented writing.

Nearly all conifers are evergreens, meaning they retain leaves throughout the year. Even during winter, they perform a limited amount of photosynthesis on sunny days. And when spring comes, conifers already have fully developed leaves that can take advantage of the sunnier days. The needle-shaped leaves of pines and firs are also adapted to survive dry seasons. A thick cuticle covers the leaf, and the stomata are located in pits, further reducing water loss.

Coniferous forests are highly productive; you probably use products harvested from them every day. For example, conifers provide much of our lumber for building and wood pulp for paper production. What we call wood is actually an accumulation of vascular tissue with lignin, which gives the tree structural support.

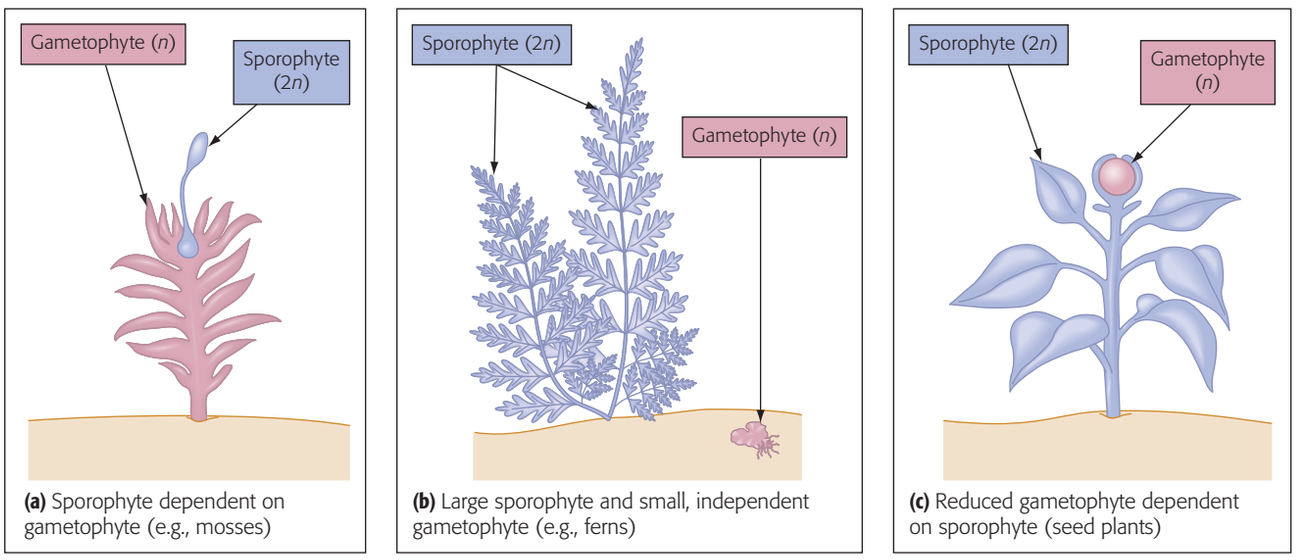


▼ Figure 16.13 A coniferous forest in Tetlin National Wildlife Refuge, Alaska. Coniferous forests are widespread in northern North America and Eurasia; conifers also grow in the Southern Hemisphere, though they are less numerous there.

Terrestrial Adaptations of Seed Plants

Compared with ferns, most gymnosperms have three additional adaptations that make survival in diverse terrestrial habitats possible: (1) further reduction of the gametophyte, (2) pollen, and (3) seeds.

The first adaptation is an even greater development of the diploid sporophyte compared with the haploid gametophyte generation **(Figure 16.14)**. A pine tree or other conifer is actually a sporophyte with tiny



► Figure 16.14 Three variations on alternation of generations in plants.

gametophytes living in its cones (Figure 16.15). In contrast to what is seen in bryophytes and ferns, gymnosperm gametophytes are totally dependent on and protected by the tissues of the parent sporophyte.

A second adaptation of seed plants to dry land came with the evolution of pollen. A **pollen grain** is actually the much-reduced male gametophyte; it houses cells that will develop into sperm. In the case of conifers, wind carries the pollen from male to female cones, where eggs develop within female gametophytes. This mechanism for sperm transfer contrasts with the swimming sperm of mosses and ferns. In seed plants, this use of tough, airborne pollen that carries sperm to egg is a terrestrial adaptation that led to even greater success and diversity of plants on land.

The third important terrestrial adaptation of seed plants is the seed itself. A seed consists of a plant embryo packaged along with a food supply within a protective coat. Seeds develop from structures called **ovules** (Figure 16.16). In conifers, the ovules are located on the scales of female cones. Conifers and other gymnosperms, lacking ovaries, bear their seeds "naked" on the cone scales (though the seeds do have protective coats). Once released from the parent plant, the seed can remain dormant for days, months, or even years. Under favorable conditions, the seed can then **germinate**, or sprout: Its embryo emerges through the seed coat as a seedling. Some seeds drop close to their parents, while others are carried far by the wind or animals. ☑

Figure 16.15 A pine tree, the sporophyte, bearing two types of cones containing gametophytes. Each scale of the female cone is actually a modified leaf that bears a structure called an ovule containing a female gametophyte. Male cones release clouds of millions of pollen grains, the male gametophytes. Some of these pollen grains land on female cones on trees of the same species. The sperm can fertilize eggs in the ovules of the female cones. The ovules eventually develop into seeds.

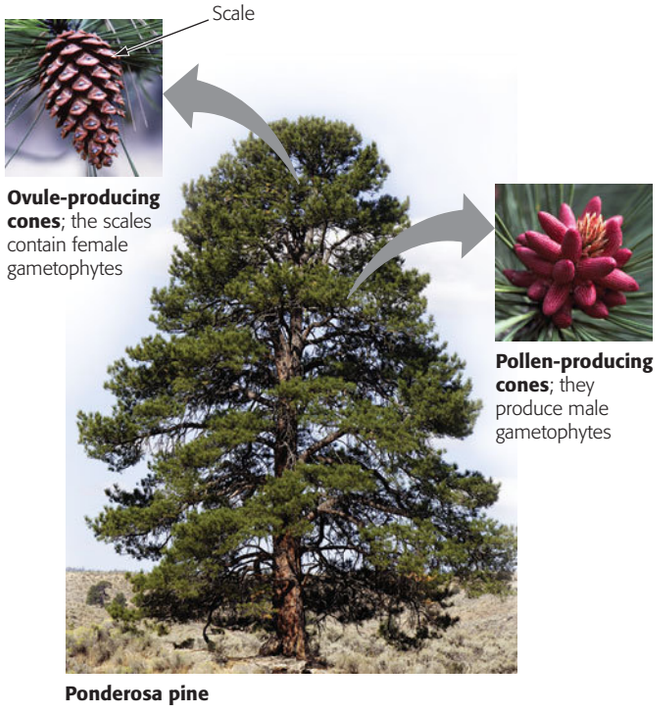
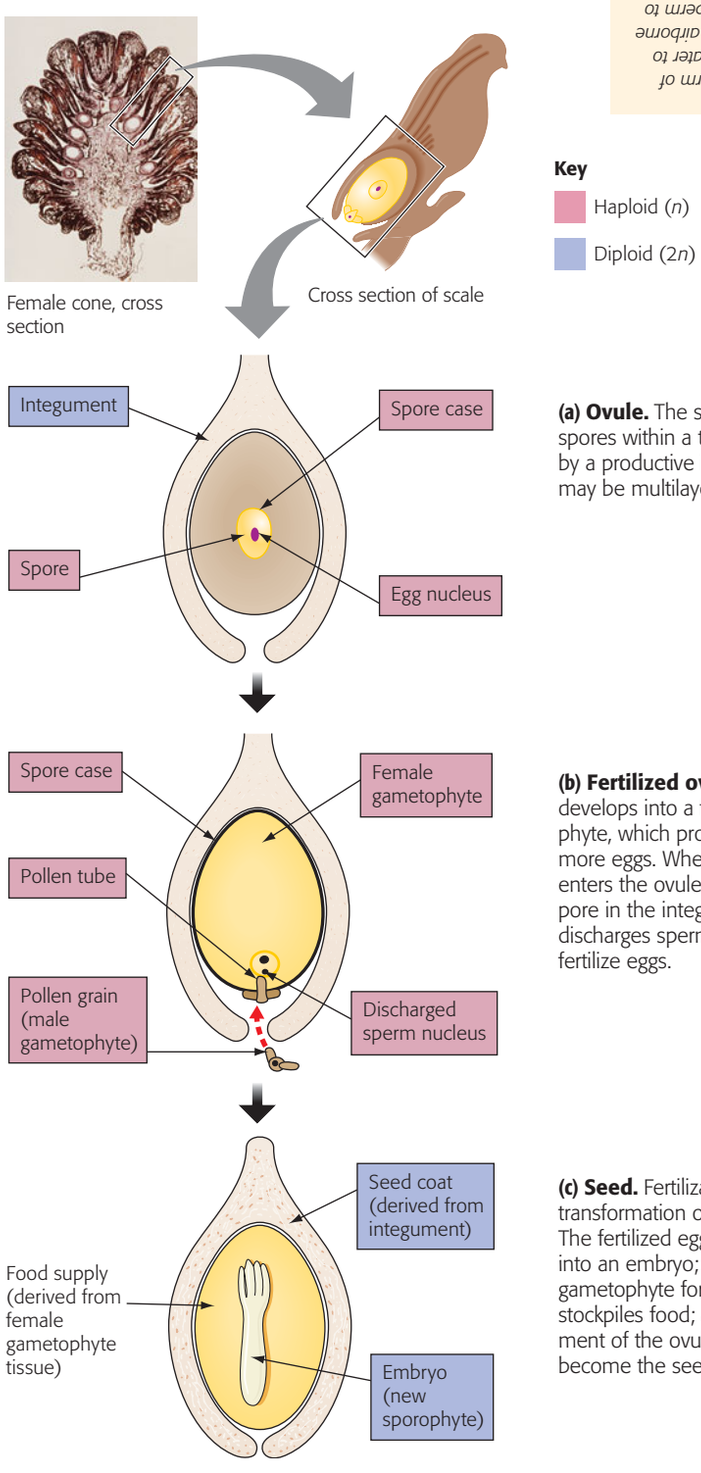


Figure 16.16 From ovule to seed.



(a) Ovule. The sporophyte produces spores within a tissue surrounded by a productive integument, which may be multilayered.

(b) Fertilized ovule. The spore develops into a female gametophyte, which produces one or more eggs. When a pollen grain enters the ovule through a special pore in the integument, it discharges sperm cells that fertilize eggs.

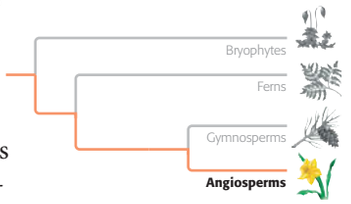
(c) Seed. Fertilization initiates the transformation of ovule to seed. The fertilized egg (zygote) develops into an embryo; the rest of the gametophyte forms a tissue that stockpiles food; and the integument of the ovule hardens to become the seed coat.

☑ CHECKPOINT

Contrast the modes of sperm delivery in ferns and conifers.

Answer: The flagellated sperm of ferns must swim through water to reach eggs. In contrast, the airborne pollen of conifers delivers sperm to eggs in ovules without the need to go through water.

Angiosperms

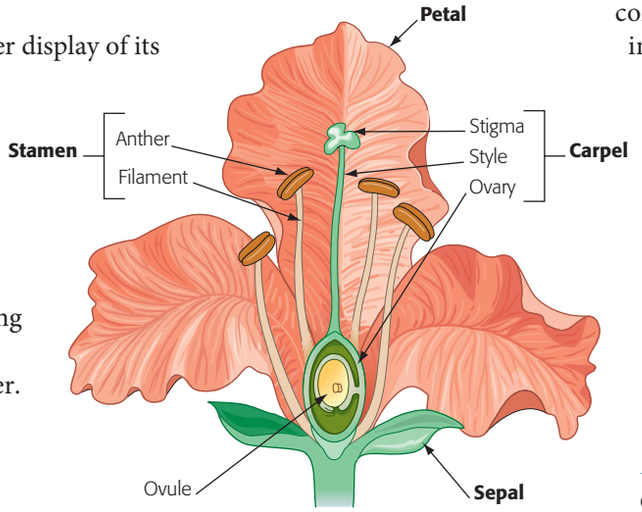


Angiosperms dominate the modern landscape. There are about 250,000 angiosperm species versus about 700 species of gymnosperms. Several unique adaptations account for the success of angiosperms. For example, refinements in vascular tissue make water transport even more efficient in angiosperms than in gymnosperms. Of all terrestrial adaptations, however, it is the flower that accounts for the unparalleled success of the angiosperms.

Flowers, Fruits, and the Angiosperm Life Cycle

No organism makes a showier display of its sex life than the angiosperm. From roses to dandelions, flowers display a plant's sex organs. For many angiosperms, this showiness helps to attract insects and other animals that transfer pollen from the sperm-bearing organs of one flower to the egg-bearing organs of another. This dependence on animals for pollen transfer targets the pollen to other plants of the same species, rather than relying on uncertain winds to blow the pollen around.

A flower is a short stem bearing modified leaves that are attached in concentric circles at its base (Figure 16.17). The outer layer consists of the **sepals**, which are usually green. They enclose the flower before it opens (think of the green "wrapping" on a rosebud). When the sepals are peeled away, the next layer is the **petals**, which are often colorful and help to attract insects and other pollinators. Plucking off the petals reveals the **stamens**, the male reproductive structures. Pollen grains develop in the **anther**, a sac at the top of each stamen. At the center of the flower is the **carpel**, the female reproductive structure. It includes the **ovary**, a protective chamber containing one or more ovules, in which eggs develop. The sticky tip of the carpel, called the **stigma**, traps pollen. As you can see in Figure 16.18, the basic structure of a flower can exist in many beautiful variations.



◄ **Figure 16.17 Structure of a flower.**

▼ **Figure 16.18 A diversity of flowers.**



Pansy



Bleeding heart



California poppy



Water lily

Figure 16.19 **The angiosperm life cycle.**

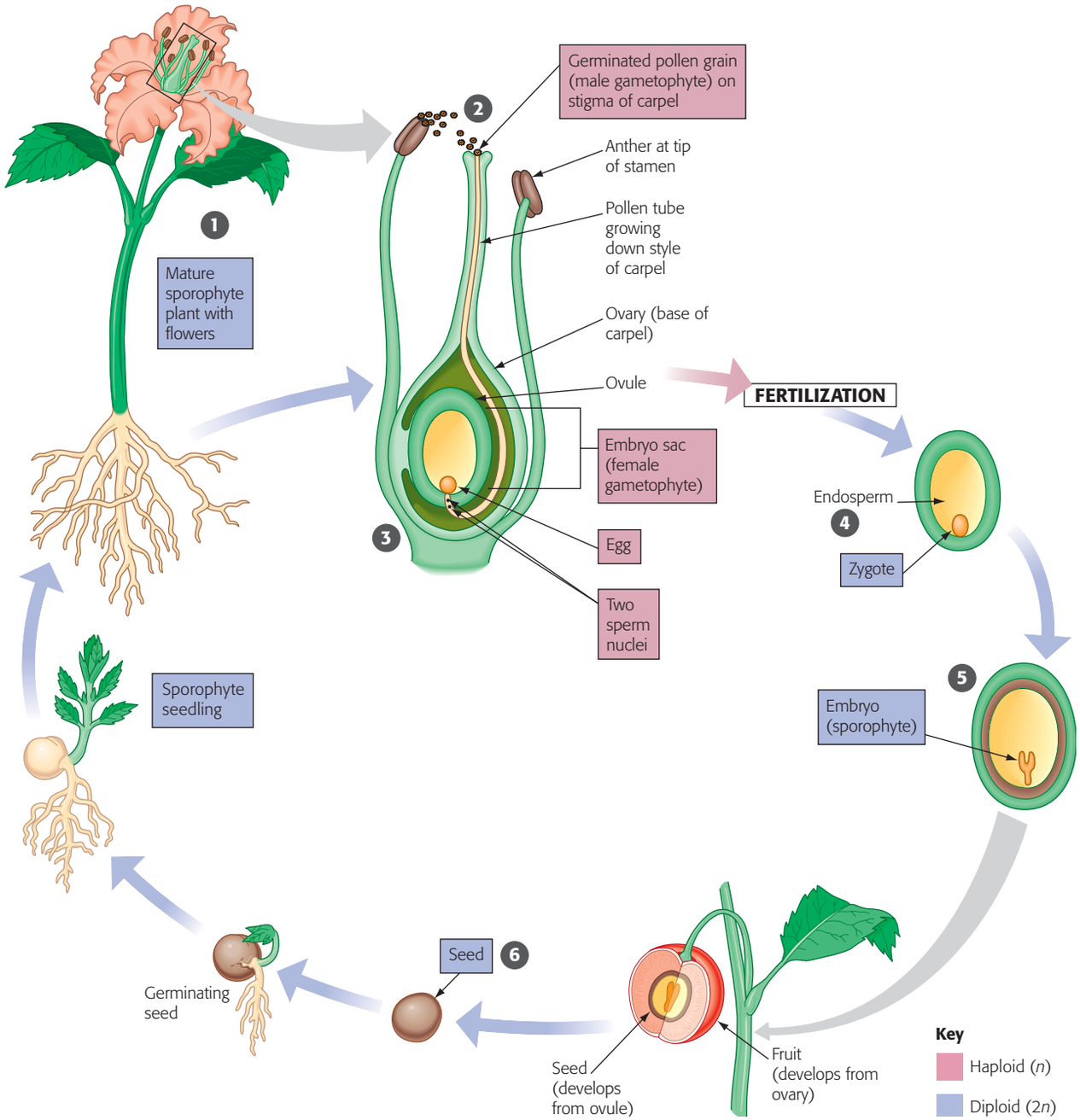


Figure 16.19 highlights key stages in the angiosperm life cycle. 1 The flower is part of the sporophyte plant. As in gymnosperms, the pollen grain is the male gametophyte of angiosperms. The female gametophyte—the embryo sac—is located within an ovule, which in turn resides within a chamber of the ovary. 2 A pollen grain that lands on the sticky stigma of a carpel extends a tube down to the ovule and 3 deposits two sperm nuclei within the embryo sac. This **double fertilization** is an angiosperm characteristic. One sperm cell fertilizes an egg in the embryo sac. 4 This produces a zygote, which 5 develops into an embryo. The second sperm cell "fertilizes" another female gametophyte cell, which then develops into a nutrient-storing tissue called **endosperm**, which nourishes the embryo. Double fertilization therefore synchronizes the development of the embryo and food reserves within an ovule. 6 The whole ovule develops into a seed. The seed's enclosure within an ovary is what distinguishes angiosperms from gymnosperms, which have a naked seed.

Why does it take two sperm to fertilize a flower?

A **fruit** is the ripened ovary of a flower. As seeds are developing from ovules, the ovary wall thickens, forming the fruit that encloses the seeds. A pea pod is an example of a fruit with seeds (mature ovules, the peas) encased in the ripened ovary (the pod). Fruits protect and help disperse seeds. As **Figure 16.20** demonstrates, many angiosperms depend on animals to disperse seeds. Conversely, most land animals, including humans, rely on angiosperms as a food source, directly or indirectly. ☑

When is a vegetable also a fruit?

☑ CHECKPOINT

What are the four main parts of a flower? Where do pollen grains develop? Where do eggs develop?

Answer: sepals, petals, stamens, carpels; in the anther within the stamen; in the ovary within the carpel

Angiosperms and Agriculture

Whereas gymnosperms supply most of our lumber and paper, angiosperms supply nearly all of our food—as well as the food eaten by domesticated animals, such as cows and chickens. Over 90% of the plant kingdom is made up of angiosperms, including cereal grains such as wheat and corn, citrus and other fruit trees, coffee and tea, and cotton. Many types of garden produce—tomatoes, squash, strawberries, and oranges, to name just a few—are the edible fruits of plants we have domesticated. Fine hardwoods from flowering plants such as oak, cherry, and walnut trees supplement the lumber we get from conifers. We also grow angiosperms for fiber, medications, perfumes, and decoration.

Early humans probably collected wild seeds and fruits. Agriculture gradually developed as people began sowing seeds and cultivating plants to have a more dependable food source. And as they domesticated certain plants, people began to select those with improved yield and quality. Agriculture can thus be seen as yet another facet of the evolutionary relationship between plants and animals.

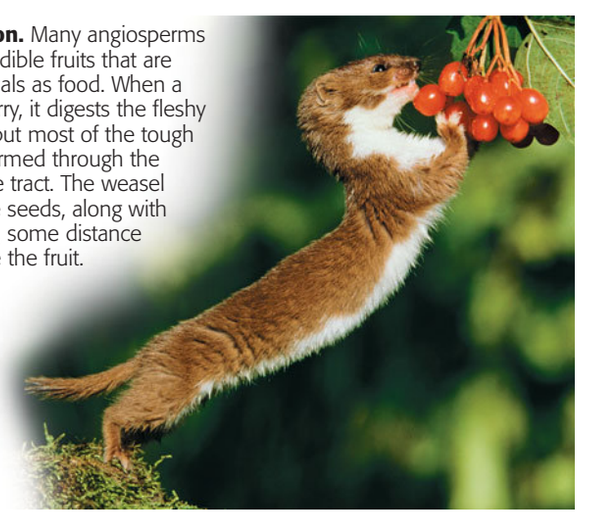
▼ Figure 16.20 Fruits and seed dispersal. Different types of fruits are adapted for different methods of dispersal.



Wind dispersal. Some angiosperms depend on wind for seed dispersal. Here, milkweed pods open to release masses of seeds (brown) carried by silken parachutes (part of the seed coat).



Animal transportation. Some fruits are adapted to hitch free rides on animals. The cockleburs attached to the fur of this dog may be carried miles before opening and releasing seeds.



Animal ingestion. Many angiosperms produce fleshy, edible fruits that are attractive to animals as food. When a weasel eats a berry, it digests the fleshy part of the fruit, but most of the tough seeds pass unharmed through the animal's digestive tract. The weasel later deposits the seeds, along with a fertilizer supply, some distance from where it ate the fruit.

Plant Diversity as a Nonrenewable Resource

The exploding human population, with its demand for space and natural resources, is extinguishing plant species at an unprecedented rate. The problem is especially critical in the tropics, where more than half the human population live and population growth is fastest. Tropical rain forests are being destroyed at a frightening pace. The most common cause of this destruction is large-scale slash-and-burn clearing of forest for agricultural use **(Figure 16.21)**. Fifty million acres, an area about the size of the state of Washington, are cleared each year, a rate that could completely eliminate Earth's tropical forests within 25 years. As the forest disappears, so do species of plants that are found nowhere else. Insects and other rain forest animals that depend on these plants are also vanishing. The toll is greatest in the tropics because that is where most species live; but environmental assault seems to be a general human tendency. Europeans eliminated most of their forests centuries ago, and habitat destruction is now endangering many species in North America. What is lost is irreplaceable—entire ecosystems that provide medicinal plants, food, timber, and clean water and air.

Many people have ethical concerns about contributing to the extinction of living forms. But there are also practical reasons to be concerned about the loss of plant diversity. As already mentioned, we depend on plants for thousands of products, including food, building materials, and medicines **(Table 16.1)**. More than 120 prescription drugs are extracted from plants. However, researchers have investigated only a fraction of the 300,000 known plant species as potential sources of medicine. Pharmaceutical companies were led to most of these species by local peoples who use the plants in preparing their traditional medicines.

Scientists are now rallying to slow the loss of plant diversity, in part by offering less destructive ways for people to benefit from forests. The goal of such efforts is to encourage management practices that use forests as resources without damaging them. The solutions we propose must be economically realistic; people who live where there are tropical rain forests must be able to make a living. But if the only goal is profit for the short term, then we will continue to slash and burn until the forests are gone. We need to appreciate the rain forests and other ecosystems as living treasures that can regenerate only slowly. Only then will we learn to work with them in ways that preserve their biological diversity for the future.

Throughout our survey of plants in this chapter, we have seen how entangled the botanical world is with other terrestrial life. We switch our attention now to that other group of organisms that moved onto land with plants: the kingdom Fungi. ☑

☑ CHECKPOINT

In what way are forests renewable resources? In what way are they not?

Answer: Forests are renewable in the sense that new trees can grow where old growth has been removed by logging. Habitats that are permanently destroyed cannot be replaced, however, so forests must be harvested in a sustainable manner.

▼ Figure 16.21 Slash-and-burn clearing of a tropical forest in Brazil.

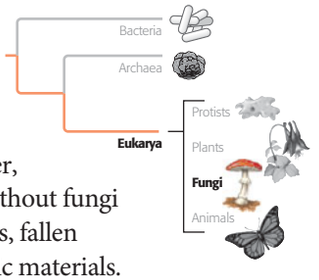


Table 16.1 A Sampling of Medicines Derived from Plants

Compound	Source	Example of Use
Atropine	Belladonna plant	Pupil dilator in eye exams
Digitalin	Foxglove	Heart medication
Menthol	Eucalyptus tree	Ingredient in cough medicines
Morphine	Opium poppy	Pain reliever
Quinine	Quinine tree	Malaria preventive
Paclitaxel (Taxol)	Pacific yew	Ovarian cancer drug
Tubocurarine	Curare tree	Muscle relaxant during surgery
Vinblastine	Periwinkle	Leukemia drug

Source: Adapted from Randy Moore et al., Botany, *2nd ed. Dubuque, IA: Brown, 1998, Table 2.2, p. 37.*

Fungi



The word *fungus* often evokes unpleasant images. Fungi rot timbers, spoil food, and afflict people with athlete's foot and worse. However, ecosystems would collapse without fungi to decompose dead organisms, fallen leaves, feces, and other organic materials. Fungi recycle vital chemical elements back to the environment in forms that other organisms can assimilate. And you have already learned that nearly all plants have mycorrhizae, fungus-root associations that help plants absorb minerals and water from the soil. In addition to these ecological roles, fungi have been used by people in various ways for centuries. We eat fungi (mushrooms and truffles, for instance), culture fungi to produce antibiotics and other drugs, add them to dough to make bread rise, culture them in milk to produce a variety of cheeses, and use them to ferment beer and wine.

Fungi are eukaryotes, and most are multicellular, but many have body structures and modes of reproduction unlike those of any other organism **(Figure 16.22)**. Molecular studies indicate that fungi and animals arose from a common ancestor around 1.5 billion years ago. The oldest undisputed fossils of fungi, however, are only about 460 million years old, perhaps because the ancestors of terrestrial fungi were microscopic and fossilized poorly. Despite appearances, a mushroom is more closely related to you than it is to any plant!

Biologists who study fungi have described over 100,000 species, and there may be as many as 1.5 million. Classifying fungi is an ongoing area of research. (One widely accepted phylogenetic tree divides the kingdom Fungi into five groups.) You are probably familiar with several kinds of fungi, including mushrooms, mold, and yeast. In this section, we'll discuss the characteristics common to all fungi and then survey their wide-ranging ecological impact. ☑

☑ CHECKPOINT

Name three ways that we benefit from fungi in our environment.

Answer: Fungi help recycle nutrients by decomposing dead organisms; mycorrhizae help plants absorb water and nutrients; some fungi serve us as food.

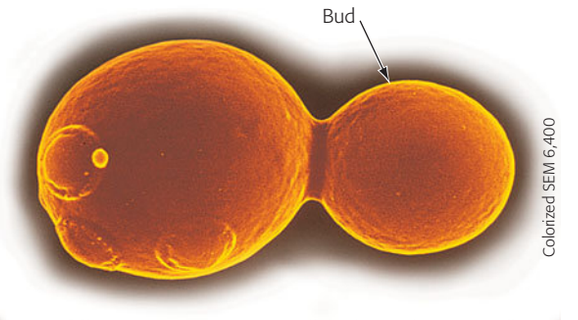
▼ Figure 16.22 A gallery of diverse fungi.



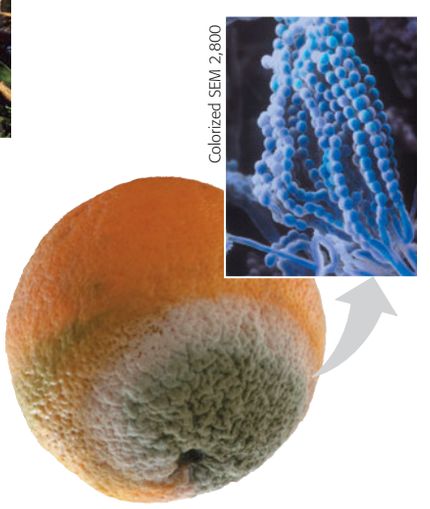
Orange fungi. These are the reproductive structures of a fungus that absorbs nutrients as it decomposes a fallen tree on a forest floor.



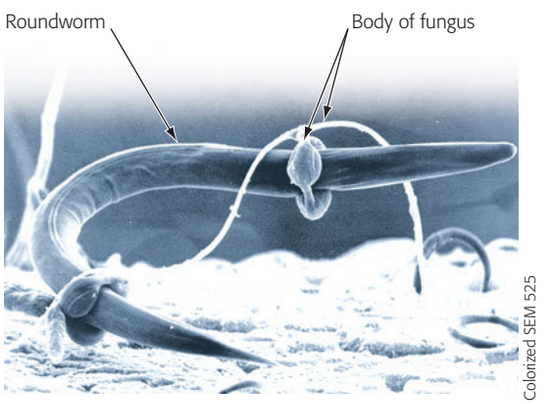
A "fairy ring." Some mushroom-producing fungi poke up "fairy rings," which can appear on a lawn overnight. A ring develops at the edge of the main body of the fungus, which consists of an underground mass of tiny filaments (hyphae) within the ring. As the underground fungal mass grows outward from its center, the diameter of the fairy ring produced at its expanding perimeter increases annually.



Budding yeast. Yeasts are unicellular fungi. This yeast cell is reproducing asexually by a process called budding.



Mold. Molds grow rapidly on their food sources, which are often our food sources as well. The mold on this orange reproduces asexually by producing chains of microscopic spores (inset) that are dispersed via air currents.



Predatory fungus. This predatory fungus traps and feeds on tiny roundworms in the soil. The fungus is equipped with hoops that can constrict around a worm in less than a second.

Characteristics of Fungi

We'll begin our look at the structure and function of fungi with an overview of how fungi obtain nutrients.

Fungal Nutrition

Fungi are chemoheterotrophs (see Figure 15.12) that acquire their nutrients by **absorption**. In this mode of nutrition, small organic molecules are absorbed from the surrounding medium. A fungus digests food outside its body by secreting powerful digestive enzymes into the food. The enzymes decompose complex molecules to simpler compounds that the fungus can absorb. Fungi absorb nutrients from such nonliving organic material as fallen logs, animal corpses, and the wastes of live organisms.

Fungal Structure

The bodies of most fungi are constructed of thread-like filaments called **hyphae** (singular, *hypha*). Fungal hyphae are minute threads of cytoplasm surrounded by a plasma membrane and cell wall. The cell walls of fungi differ from the cellulose walls of plants. Fungal cell walls are usually built mainly of chitin, a strong but flexible polysaccharide that is also found in the external skeletons of insects. Most fungi have multicellular hyphae, which consist of chains of cells separated by cross-walls with pores. In many fungi, cell-to-cell channels allow ribosomes, mitochondria, and even nuclei to flow between cells.

Fungal hyphae branch repeatedly, forming an interwoven network called a **mycelium** (plural, *mycelia*), the feeding structure of the fungus **(Figure 16.23)**. Fungal mycelia usually escape our notice because they are often subterranean, but they can be huge. In fact, scientists have discovered that the mycelium of one humongous fungus in Oregon is 5.5 km—that's 3.4 miles!—in diameter and spreads through 2,200 acres of forest. This fungus is at least 2,600 years old and weighs hundreds of tons, qualifying it as one of Earth's oldest and largest organisms.

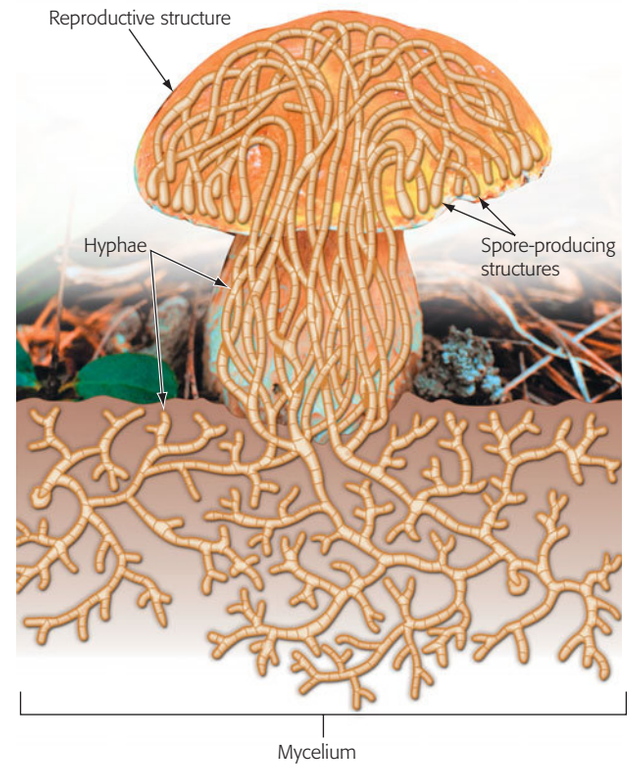
A mycelium maximizes contact with its food source by mingling with the organic matter it is decomposing and absorbing. A bucketful of rich organic soil may contain as much as a kilometer of hyphae. A fungal mycelium grows rapidly, adding hyphae as it branches within its food. The great majority of fungi are nonmotile; they cannot run, swim, or fly in search of food. But the mycelium makes up for the lack of mobility by swiftly extending the tips of its hyphae into new territory. ☑

Fungal Reproduction

The mushroom in Figure 16.23 is actually made up of tightly packed hyphae. Mushrooms arise from an underground mycelium. While the mycelium obtains food from organic material via absorption, the function of the mushroom is reproduction. Unlike a truffle, which employs animals to disperse its spores, a mushroom pops up above ground to disperse its spores on air currents.

Fungi typically reproduce by releasing haploid spores that are produced either sexually or asexually. The output of spores is mind-boggling. For example, puffballs, which are the reproductive structures of certain fungi, can spew clouds containing trillions of spores. Easily carried by wind or water, spores germinate to produce mycelia if they land in a moist place where there is food. Spores thus function in dispersal and account for the wide geographic distribution of many species of fungi. The airborne spores of fungi have been found more than 160 km (100 miles) above Earth. Closer to home, try leaving a slice of bread out for a week and you will observe the furry mycelia that grow from the invisible spores raining down from the surrounding air.

How does bread get moldy?





◄ Figure 16.23 The fungal mycelium. A mushroom consists of tightly packed hyphae that extend upward from a much more massive mycelium of hyphae growing underground. The photo shows a mycelium made up of the cottony threads that decompose organic litter.

☑ CHECKPOINT

Describe how the structure of a fungal mycelium reflects its function.

Answer: The extensive network of hyphae puts a large surface area in contact with the food source.

The Ecological Impact of Fungi

Fungi have been major players in terrestrial communities ever since plants and fungi together moved onto land. Let's examine a few examples of how fungi continue to have an enormous ecological impact, including numerous interactions with people.

Fungi as Decomposers

Fungi and bacteria are the principal decomposers that keep ecosystems stocked with the inorganic nutrients essential for plant growth. Without decomposers, carbon, nitrogen, and other elements would accumulate in nonliving organic matter. Plants and the animals they feed would starve because elements taken from the soil would not be returned.

Fungi are well adapted as decomposers of organic refuse. Their invasive hyphae enter the tissues and cells of dead organisms and digest polymers, including the cellulose of plant cell walls. A succession of fungi, in concert with bacteria and, in some environments, invertebrate animals, is responsible for the complete breakdown of organic litter. The air is so loaded with fungal spores that as soon as a leaf falls or an insect dies, it is covered with spores and soon after infiltrated by fungal hyphae.

What kind of "worm" is actually a fungus?

We may applaud fungi that decompose forest litter or dung, but it's a different story when molds attack our fruit or our shower curtains. A significant amount of the world's fruit harvest is lost each year to fungal attack. And a wood-digesting fungus does not distinguish between a fallen oak limb and the oak planks of a boat. During the Revolutionary War, the British lost more ships to fungal rot than to enemy attack. What's more, soldiers stationed in the tropics during World War II watched as their tents, clothing, boots, and binoculars were destroyed by molds.

Parasitic Fungi

Parasitism is a relationship in which two species live in contact and one organism benefits while the other is harmed. Parasitic fungi absorb nutrients from the cells or body fluids of living hosts. Of the 100,000 known species of fungi, about 30% make their living as parasites.

About 50 species of fungi are known to be parasitic in humans and other animals. Among the diseases that fungi cause in people are yeast infections of the lungs, some of which can be fatal, and vaginal yeast infections. Other fungal parasites produce a skin disease called ringworm, so named because it appears as circular red areas on the skin. Most commonly, ringworm fungus attacks the feet and causes intense itching and sometimes blisters. This condition, known as athlete's foot, is highly contagious but can be treated with fungicidal lotions and powders.

The great majority of fungal parasites infect plants. In some cases, fungi that infect plants have literally changed the landscape. For example, American chestnut and American elm trees, once common in forests, fields, and city streets, were devastated by fungal epidemics **(Figure 16.24a)**. Fungi are also serious agricultural pests, and some of the fungi that attack food crops are toxic to humans. The seed heads of many kinds of grain and grasses, including rye, wheat, and oats, are sometimes infected with fungal growths called ergots **(Figure 16.24b)**. Consumption of flour made from ergot-infested grain can cause hallucinations, temporary insanity, and death. In fact, lysergic acid, the raw material from which the hallucinogenic drug LSD is made, has been isolated from ergots. This fact may help explain a centuries-old mystery, as we'll see next.



(a) An American elm tree killed by Dutch elm disease fungus



(b) Ergots

◄ Figure 16.24 Parasitic fungi that cause plant disease. (a) The parasitic fungus that causes Dutch elm disease evolved with European species of elm trees, and it is relatively harmless to them. But it has been deadly to American elms since it was accidentally introduced after World War I. (b) Ergots, parasitic fungi, are the dark structures on these rye seed heads.



Plant-Fungus Symbiosis **THE PROCESS OF SCIENCE**

Did a Fungus Lead to the Salem Witch Hunt?

In January 1692, eight young girls in the town of Salem, Massachusetts, began to act bizarrely. The girls suffered from incomprehensible speech, odd skin sensations, convulsions, and hallucinations. The worried community blamed the girls' symptoms on witchcraft and began to accuse one another. By the time the hysteria ended that autumn, more than 150 villagers had been accused of witchcraft, and 20 of them had been hanged. Finding the cause behind the "Salem witch hunt" has long intrigued historians.

In 1976, a University of California psychology graduate student offered a new explanation. She began with the **observation** that the symptoms reported by the girls were consistent with ergot poisoning **(Figure 16.25)**. This led her to **question** whether an ergot outbreak could have been behind the witch hunt. The researcher tested her **hypothesis** by examining the historical records, making the **prediction** that facts consistent with ergot poisoning would be uncovered.

Her **results** were suggestive, though not conclusive. Agricultural records confirm that rye—the principal host for ergot—grew abundantly around Salem at that time and that the growing season of 1691 had been particularly warm and wet, conditions under which ergot thrives. This suggests that the rye crop consumed during the winter of 1691–1692 could easily have been contaminated. The summer of 1692, when the accusations began to die down, was dry, consistent with an ergot die-off. Most importantly, the reported symptoms appear consistent with those of ergot poisoning. These clues suggest (but do not prove) that the girls, and perhaps others in Salem, were in the grips of ergot-induced illness. Some historians dispute this idea, and other hypotheses have been proposed. Conclusive evidence may never be found, but this story reinforces the unifying thread of this chapter—the importance of the interaction of plants and fungi—and illustrates how the scientific method can be applied in a wide variety of academic disciplines.

▼ Figure 16.25 Ergot and the Salem witch hunt. Ergot poisoning may have been the catalyst for the Salem witch hunt of 1692.



Commercial Uses of Fungi

It would not be fair to fungi to end our discussion with an account of diseases. In addition to their positive global impact as decomposers, fungi also have a number of practical uses for people.

Most of us have eaten mushrooms, although we may not have realized that we were ingesting the reproductive extensions of subterranean fungi. Your grocery store probably stocks Portobello, shiitake, and oyster mushrooms along with common button mushrooms. If you like to cook with mushrooms, you can buy a mushroom "garden"—mycelium embedded in a rich food source—that makes it easy to grow your own. Some enthusiasts gather edible fungi from fields and forests **(Figure 16.26)**, but only experts should dare to eat wild fungi. Some poisonous species resemble edible ones, and there are no simple rules to help the novice distinguish one from the other.

Other fungi are used in food production. The distinctive flavors of certain kinds of cheeses, including Roquefort and blue cheese, come from the fungi used to ripen them. And people have used yeasts (unicellular fungi) for thousands of years to produce alcoholic beverages and cause bread to rise (see Figure 6.16).

▼ Figure 16.26 Fungi eaten by people.



Chicken of the woods. This fleshy shelf fungus is said to taste like chicken.



Chanterelle mushrooms. Gourmet mushrooms are highly prized by chefs for their earthy flavors and interesting textures.



Giant puffball. These humongous fungi can grow to more than 2 feet in diameter. They are only edible when immature, before the spores form. Beware: Deadly fungi often resemble small puffballs.

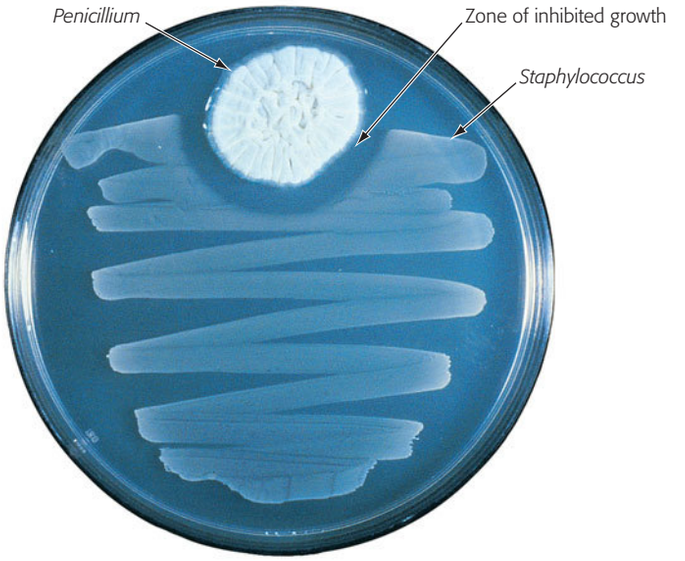
☑ CHECKPOINT

1. What is athlete's foot?
2. What do you think is the natural function of the antibiotics that fungi produce in their native environments?

Answers: **1.** *Athlete's foot is infection of the foot's skin with ringworm fungus.* **2.** *The antibiotics block the growth of microorganisms, especially bacteria, that compete with the fungi for nutrients and other resources.*

Fungi are medically valuable as well. Some fungi produce antibiotics that are used to treat bacterial diseases. In fact, the first antibiotic discovered was penicillin, made by the common mold *Penicillium* **(Figure 16.27)**. And in 2007, researchers discovered that several varieties of fungi that attack hazelnut trees produce a powerful anticancer drug.

As sources of medicines and food, as decomposers, and as partners with plants in mycorrhizae, fungi play vital roles in life on Earth. ☑



► **Figure 16.27 Fungal production of an antibiotic.** Penicillin is made by the common mold *Penicillium*. In this petri dish, the clear area between the mold and the growing *Staphylococcus* bacteria is where the antibiotic produced by the *Penicillium* inhibits the growth of the bacteria.



Plant-Fungus Symbiosis EVOLUTION CONNECTION

Mutually Beneficial Symbiosis

Discussing fungi in the same chapter as plants may seem to indicate that these two kingdoms are close relatives. Actually, as we've discussed, fungi are more closely related to animals than to plants. But the success of plants on land and the great diversity of fungi are interconnected; neither could have populated the land without the other.

Evolution is not just about the origin and adaptation of individual species. Relationships between species are also an evolutionary product. For example, prokaryotes partner with a variety of organisms in mutually beneficial symbioses. Eukaryotic cells evolved from symbiosis among prokaryotes (see Figure 15.19). Bacteria living in the roots of certain plants provide nitrogen compounds to their host and receive food in exchange. We even have our own symbiotic bacteria that help keep our skin healthy and produce certain vitamins in our intestines. Particularly relevant to this chapter is the symbiotic association of fungi and plant roots—mycorrhizae—that made life's move onto land possible.

Lichens, symbiotic associations of unicelleular algae or photosynthetic bacteria held in a mass of fungal hyphae, are striking examples of how intimate these relationships can be. At a distance, it is easy to mistake lichens for mosses or other simple plants growing on rocks, rotting logs, or trees **(Figure 16.28)**. The partners are so closely entwined that they appear to be a single organism. The fungus receives food from its photosynthetic partner. The fungal mycelium, in turn, provides a suitable habitat for the algae, helping the algae absorb and retain water and minerals. The merger is so complete that lichens are actually named as species, as though they were individual organisms.

After protists and plants, fungi is the third group of eukaryotes that we have surveyed so far. Strong evidence suggests that they evolved from protist ancestors that also gave rise to the fourth and most diverse group of eukaryotes: the animals, the topic of the next chapter.

▼ **Figure 16.28 Lichens: symbiotic associations of fungi and algae.** Lichens generally grow very slowly, sometimes less than a millimeter per year. Some lichens are thousands of years old, rivaling the oldest plants as Earth's elders. The close relationship between the fungal and algal partners is evident in the microscopic blowup of a lichen.





Chapter Review

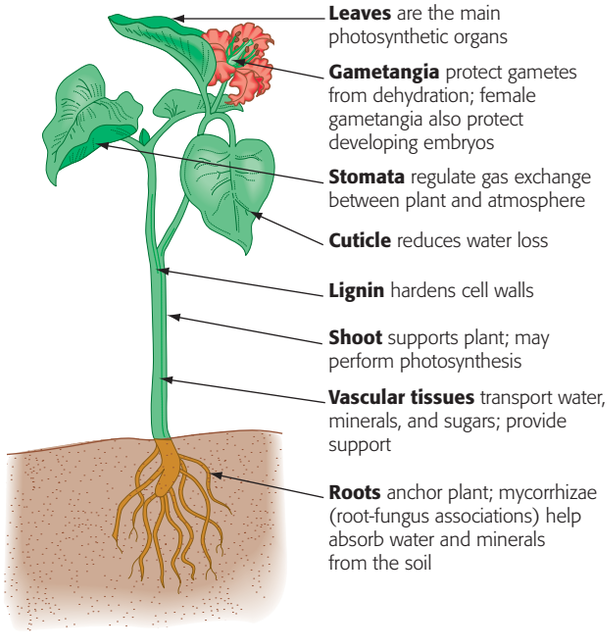
SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Colonizing Land

Terrestrial Adaptations of Plants

Plants are multicellular photosynthetic eukaryotes with adaptations for living on land.



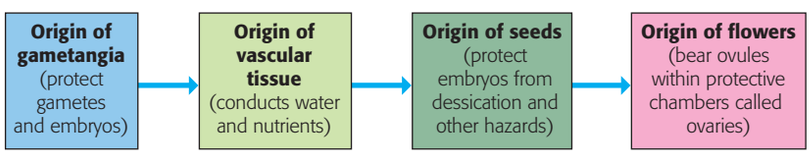
The Origin of Plants from Green Algae

Plants evolved from a group of multicellular green algae called charophytes.

Plant Diversity

Highlights of Plant Evolution

Four major periods of plant evolution are marked by terrestrial adaptations.



Bryophytes



The most familiar bryophytes are mosses. Mosses display two key terrestrial adaptations: a waxy cuticle that prevents dehydration and the retention of developing embryos within the mother plant's gametangia. Mosses are most common in moist environments because their sperm must swim to the eggs and because they lack lignin in their cell walls and thus cannot stand tall. Bryophytes are unique among plants in having the gametophyte as the dominant generation in the life cycle.

Ferns



Ferns are seedless plants that have vascular tissues but still use flagellated sperm to fertilize eggs. During the Carboniferous period, giant ferns were among the plants that decayed to thick deposits of organic matter, which were gradually converted to coal.

Gymnosperms



A drier and colder global climate near the end of the Carboniferous period favored the evolution of the first seed plants. The most successful were the gymnosperms, represented by conifers. Needle-shaped leaves with thick cuticles and sunken stomata are adaptations to dry conditions. Conifers and most other gymnosperms have three additional terrestrial adaptations: (1) further reduction of the haploid gametophyte and greater development of the diploid sporophyte, (2) sperm-bearing pollen, which doesn't require water for transport, and (3) seeds, which consist of a plant embryo packaged along with a food supply inside a protective coat.

Angiosperms



Angiosperms supply nearly all our food and much of our fiber for textiles. The evolution of the flower and more efficient water transport help account for the success of the angiosperms. The dominant stage is a sporophyte with gametophytes in its flowers. The female gametophyte is located within an ovule, which in turn resides within a chamber of the ovary. Fertilization of an egg in the female gametophyte produces a zygote, which develops into an embryo. The whole ovule develops into a seed. The seed's enclosure within an ovary is what distinguishes angiosperms from gymnosperms, which have naked seeds. A fruit is the ripened ovary of a flower. Fruits protect and help disperse seeds. Angiosperms are a major food source for animals, while animals aid plants in pollination and seed dispersal. Agriculture constitutes a unique kind of evolutionary relationship among plants, people, and other animals.

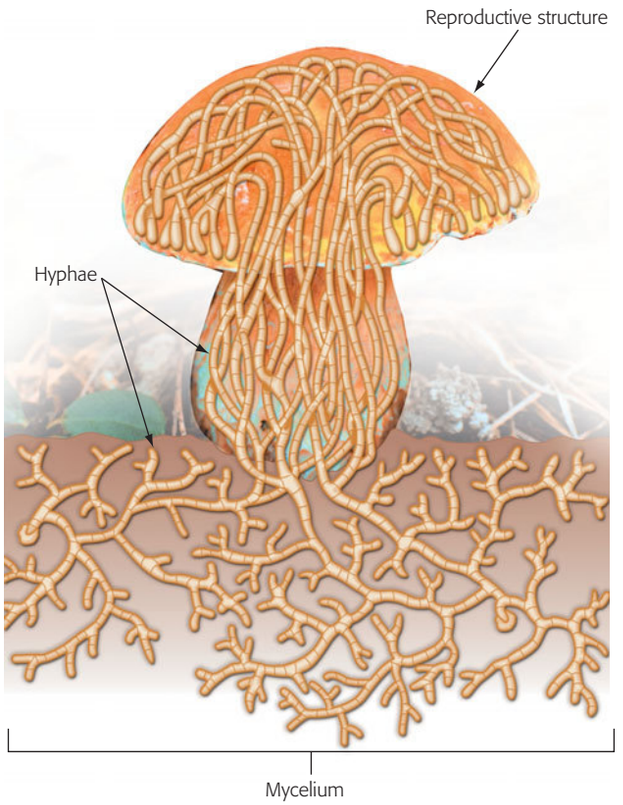
Plant Diversity as a Nonrenewable Resource

The exploding human population, with its demand for space and natural resources, is causing the extinction of plant species at an unprecedented rate. Scientists are researching how to slow this loss and help us learn to work with forests in ways that preserve their biological diversity.

Fungi

Characteristics of Fungi

Fungi are unicellular or multicellular eukaryotes; they are chemoheterotrophs that digest their food externally and absorb the nutrients from the environment. They are more closely related to animals than to plants. A fungus usually consists of a mass of threadlike hyphae, forming a mycelium. The cell walls of fungi are mainly composed of chitin. Although most fungi are nonmotile, a mycelium can grow very quickly, extending the tips of its hyphae into new territory. Mushrooms are reproductive structures that extend from the underground mycelium. Fungi reproduce and disperse by releasing spores that are produced either sexually or asexually.



The Ecological Impact of Fungi

Fungi and bacteria are the principal decomposers of ecosystems. Many molds destroy fruit, wood, and human-made materials. About 50 species of fungi are known to be parasites of people and other animals. Fungi are also commercially important as food and in baking, beer and wine production, and the manufacture of antibiotics.

Evolution Connection: Mutually Beneficial Symbiosis

Lichens, in which algae are surrounded by fungal hyphae, are an example of a mutually beneficial symbiotic relationship.

SELF-QUIZ

1. Which of the following structures is common to all four major plant groups: vascular tissue, flowers, seeds, cuticle, pollen?
2. Angiosperms are distinguished from all other plants because only angiosperms have reproductive structures called _____.
3. Complete the following analogies:
   a. Gametophyte is to haploid as _____ is to diploid.
   b. _____ are to conifers as flowers are to _____.
   c. Ovule is to seed as ovary is to _____.
4. Under a microscope, a piece of a mushroom would look most like
   a. jelly.
   b. a tangle of string.
   c. grains of sand.
   d. a sponge.
5. During the Carboniferous period, the dominant plants, which later formed the great coal beds, were mainly
   a. mosses and other bryophytes.
   b. ferns and other seedless vascular plants.
   c. charophytes and other green algae.
   d. conifers and other gymnosperms.
6. You discover a new species of plant. Under the microscope, you find that it produces flagellated sperm. A genetic analysis shows that its dominant generation has diploid cells. What kind of plant do you have?
7. How does the evergreen nature of pines and other conifers adapt the plants for living where the growing season is very short?
8. Which of the following terms includes all others in the list? angiosperm, fern, vascular plant, gymnosperm, seed plant
9. Plant diversity is greatest in
   a. tropical forests.
   b. the temperate forests of Europe.
   c. deserts.
   d. the oceans.
10. What is a fruit?
11. Lichens are symbionts of photosynthetic _____ with _____.
12. Contrast the heterotrophic nutrition of a fungus with your own heterotrophic nutrition.

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

13. In April 1986, an accident at a nuclear power plant in Chernobyl, Ukraine, scattered radioactive fallout for hundreds of miles. In assessing the biological effects of the radiation, researchers found mosses to be especially valuable as organisms for monitoring the damage. Radiation damages organisms by causing mutations. Explain why it is faster to observe the genetic effects of radiation on mosses than on other types of plants. Imagine that you are conducting tests shortly after a nuclear accident. Using potted moss plants as your experimental organisms, design an experiment to test the hypothesis that the frequency of mutations decreases with the organism's distance from the source of radiation.

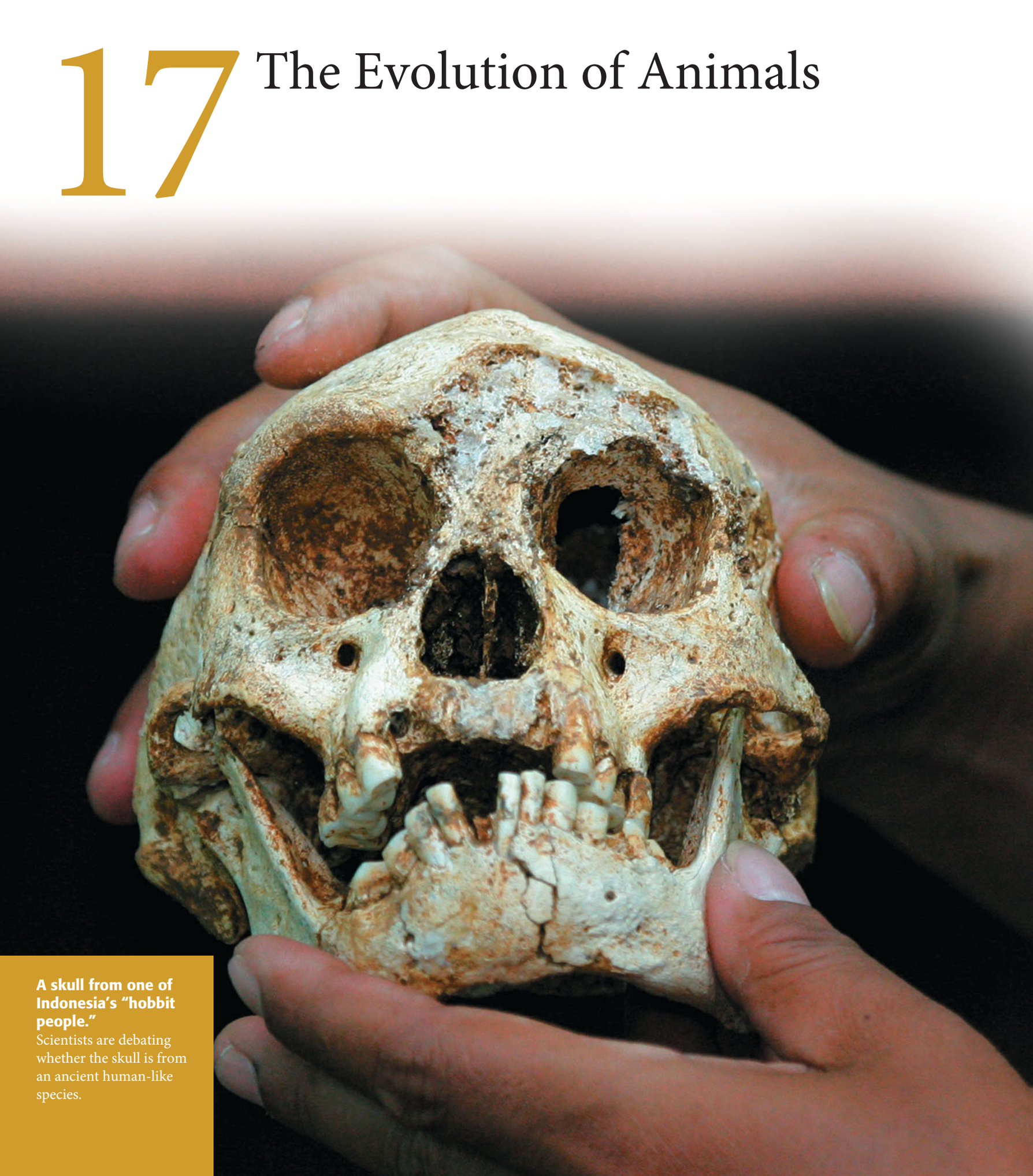
14. You discover what you think may be one extremely large underground fungal mycelium living beneath your campus. How could you prove that it is, in fact, one individual organism spread across a very large area, as opposed to a group of separate organisms?

BIOLOGY AND SOCIETY

15. Why are tropical rain forests being destroyed at such an alarming rate? What kinds of social, technological, and economic factors are responsible? Most forests in more industrialized Northern Hemisphere countries have already been cut. Do the more industrialized nations have a right to pressure the less industrialized nations in the Southern Hemisphere to slow or stop the destruction of their forests? Defend your answer. What kinds of benefits, incentives, or programs might slow the assault on the rain forests?

16. Imagine you were charged with the task of managing a coniferous forest. How would you balance the need for productive use of the forest (to provide lumber, for example) with preservation of its diversity? What activities would you allow or prohibit in the forest (for example, snowmobiling, logging, hiking, mushroom harvesting, mining, camping, grazing, making campfires)? How would you defend your choices to the public?

17 The Evolution of Animals



A skull from one of Indonesia's "hobbit people." Scientists are debating whether the skull is from an ancient human-like species.

CHAPTER CONTENTS

The Origins of Animal Diversity 338
Major Invertebrate Phyla 341
Vertebrate Evolution and Diversity 354
The Human Ancestry 361

CHAPTER THREAD
Human Evolution

BIOLOGY AND SOCIETY
The Discovery of the Hobbit People 337
THE PROCESS OF SCIENCE
Who Were the Hobbit People? 365
EVOLUTION CONNECTION
Are We Still Evolving? 367



Human Evolution BIOLOGY AND SOCIETY

The Discovery of the Hobbit People

In 2003, Australian anthropologists digging on the Indonesian island of Flores stumbled upon bones of some highly unusual people, including the nearly complete skeleton of an adult female. Next to a modern woman, this fully grown individual would stand about waist-high. Features of her skull, such as the shape and thickness of the bones, were human-like, but its size was proportional to her tiny body, and her brain was the size of a chimpanzee's. Surprisingly, the bones were accompanied by tools for hunting and butchering animals, along with evidence of cooking fires. Most astonishing of all, the remains dated to roughly 18,000 years ago, a time when scientists had thought that *Homo sapiens* was the only surviving human species. Since the initial discovery, researchers have unearthed the bones of a dozen or so more of these miniature humans.

The discoverers attributed their astonishing find to a previously unknown species, which they named *Homo floresiensis* and nicknamed "hobbits." They speculated that a band of ancestral humans arrived on Flores millions of years ago from Africa and, within the isolated environment of the island, evolved into the diminuitive *Homo floresiensis*. There is precedent for animal evolution of this type: Biologists have discovered island-bound dwarf populations of deer, elephants, and hippos. One hypothesis is that a lack of predators favors the evolution of smaller, more energy-efficient forms. Controversy erupted as soon as the team announced their findings. Skeptical scientists suggested that the bones were from *Homo sapiens* with diseases that cause skeletal malformations. As you'll find out in the Process of Science section, the more scientists learn about the "hobbit" people, the more puzzling their findings become.

Homo sapiens and *Homo floresiensis* are just two of the over 1 million species of animals that have been named and described by biologists. This amazing diversity arose through hundreds of millions of years of evolution as natural selection shaped animal adaptations to Earth's many environments. In this chapter, we'll look at the 9 most abundant and widespread of the roughly 35 phyla (major groups) in the kingdom Animalia. We'll give special attention to the major milestones in animal evolution and conclude by reconnecting with the fascinating subject of human evolution.

The Origins of Animal Diversity

Animal life began in Precambrian seas with the evolution of multicellular creatures that ate other organisms. We are among their descendants.

What Is an Animal?

Animals are eukaryotic, multicellular, heterotrophic organisms that obtain nutrients by eating. This mode of nutrition contrasts animals with plants and other organisms that construct organic molecules through photosynthesis. It also contrasts with fungi, which obtain nutrients by absorption after digesting the food outside their bodies (see Figure 16.23). Most animals digest their food within their bodies after ingesting other organisms, dead or alive, whole or by the piece **(Figure 17.1)**.

Animal cells lack the cell walls that provide strong support in the bodies of plants and fungi. And most animals have muscle cells for movement and nerve cells that control the muscles. The most complex animals can use their muscular and nervous systems for many functions other than eating. Some species even use massive networks of nerve cells called brains to think.

Most animals are diploid and reproduce sexually; eggs and sperm are the only haploid cells. The life cycle of a sea star **(Figure 17.2)** includes basic stages found in most animal life cycles. 1 Male and female adult animals make haploid gametes by meiosis, and 2 an egg and a sperm fuse, producing a zygote. 3 The zygote divides by mitosis, forming 4 an early embryonic stage called a **blastula**, which is usually a hollow ball of cells. 5 In most animals, one side of the blastula folds inward, forming a stage called a **gastrula**. 6 The gastrula develops into a saclike embryo with a two-layered wall and an opening at one end. After the gastrula stage, many animals develop directly into adults. 7 Others, such as the sea star, develop into a **larva**, an immature individual that looks different from the adult animal. (A tadpole, for another example, is a larval frog.) 8 The larva undergoes a major change of body form, called **metamorphosis**, in becoming an adult capable of reproducing sexually. ☑

☑ CHECKPOINT

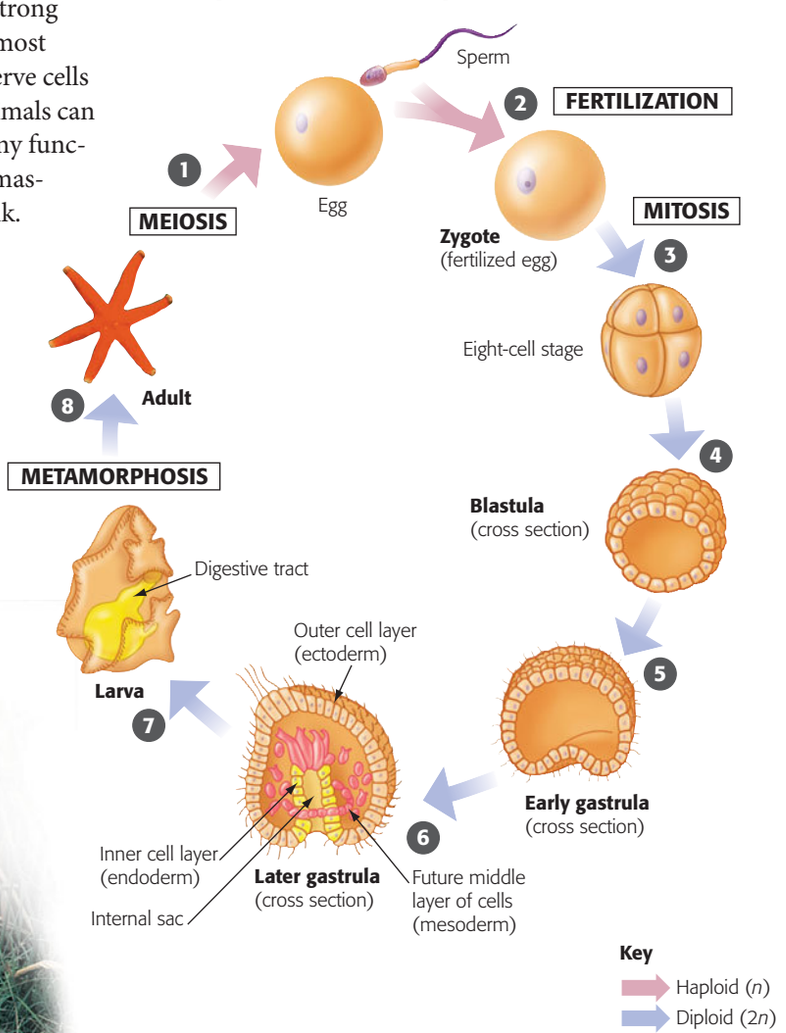
What mode of nutrition distinguishes animals from fungi, both of which are heterotrophs?

Answer: ingestion (eating)

▼ Figure 17.1 Nutrition by ingestion, the animal way of life. Few animals ingest a piece of food as large as the gazelle being eaten by this rock python. The snake will spend two weeks or more digesting its meal.



▼ Figure 17.2 The life cycle of a sea star as an example of animal development.



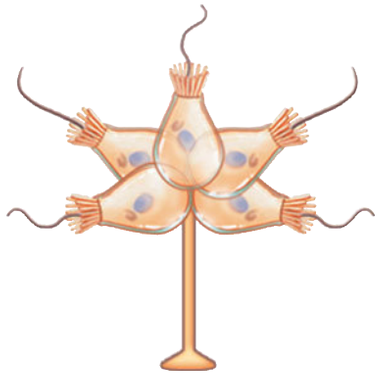
Early Animals and the Cambrian Explosion

Scientists hypothesize that animals evolved from a colonial, flagellated protist **(Figure 17.3)**. Although molecular data point to a much earlier origin, the oldest animal fossils that have been found are 550–575 million years old. Animal evolution must have already been under way for some time prior to that—the fossils reveal a variety of shapes, and sizes range from 1 cm to 1 m in length **(Figure 17.4)**.

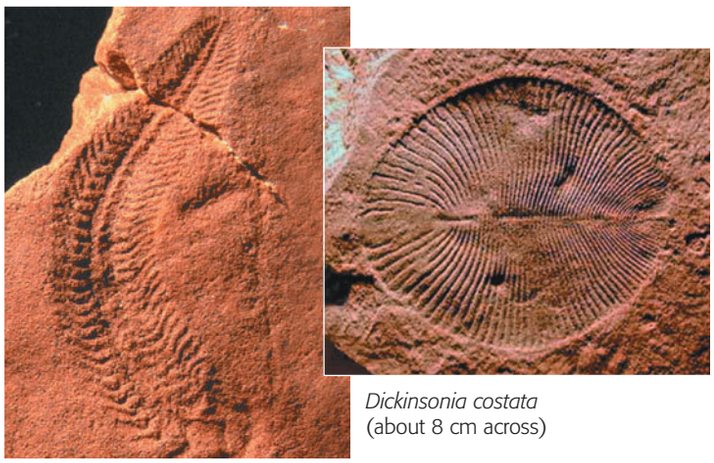
Animal diversification appears to have accelerated rapidly from 535 to 525 million years ago, during the Cambrian period. Because so many animal body plans and new phyla appear in the fossils from such an evolutionarily short time span, biologists call this episode the Cambrian explosion. The most celebrated source of Cambrian fossils is located in British Columbia, Canada. The Burgess Shale, as it is known, provided a cornucopia of perfectly preserved animal fossils. In contrast to the Precambrian animals, many Cambrian animals had hard parts such as shells, and many are clearly related to existing animal groups. For example, scientists have classified more than a third of the species found in the Burgess Shale as arthropods, the group that includes present-day crabs, shrimps, and insects **(Figure 17.5)**. Other fossils are more difficult to place. Some are downright weird, like the spiky creature near the center of the drawing, known as *Hallucigenia*, and *Opabinia*, the five-eyed predator grasping a worm with the long, flexible appendage that protrudes in front of its mouth.

What ignited the Cambrian explosion? Scientists have proposed several hypotheses, including increasingly complex predator-prey relationships and an increase in atmospheric oxygen. But whatever the cause of the rapid diversification, it is likely that the set of "master control" genes—the genetic framework for complex bodies—was already in place (see Figure 11.10). Much of the diversity in body form among the animal phyla is associated with variations in where and when these genes are expressed within developing embryos.

In the last half billion years, animal evolution has to a large degree merely generated variations of the animal forms that originated in the Cambrian seas. Continuing research will help test hypotheses about the Cambrian explosion. But even as the explosion becomes less mysterious, it will seem no less wondrous. ☑



◄ Figure 17.3 Hypothetical common ancestor of animals. As you'll learn shortly, the individual cells of this colonial flagellated protist resemble the feeding cells of sponges.

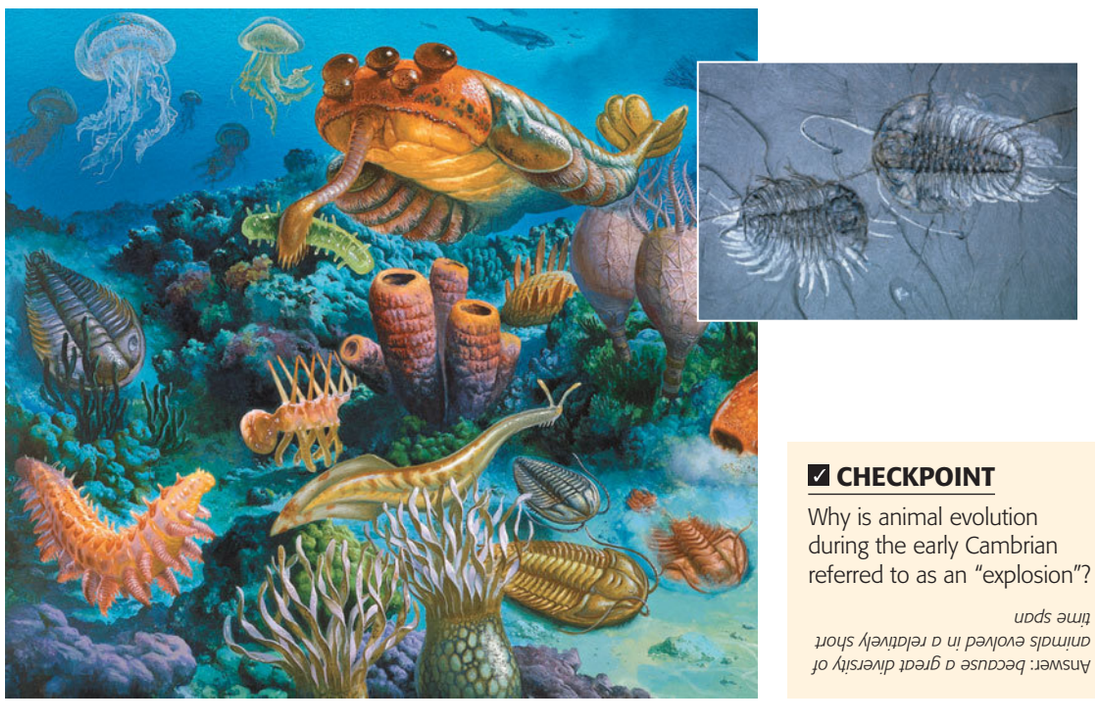


Spriggina floundersi (about 3 cm long)

Dickinsonia costata (about 8 cm across)

◄ Figure 17.4 Precambrian animals. All of the oldest animal fossils are impressions of soft-bodied animals. Most of them do not appear to be related to any living group of animals.

▼ Figure 17.5 A Cambrian seascape. This drawing is based on fossils from the Burgess Shale. The flat-bodied animals are ancient arthropods called trilobites. A photo of fossil trilobites is shown at the right.



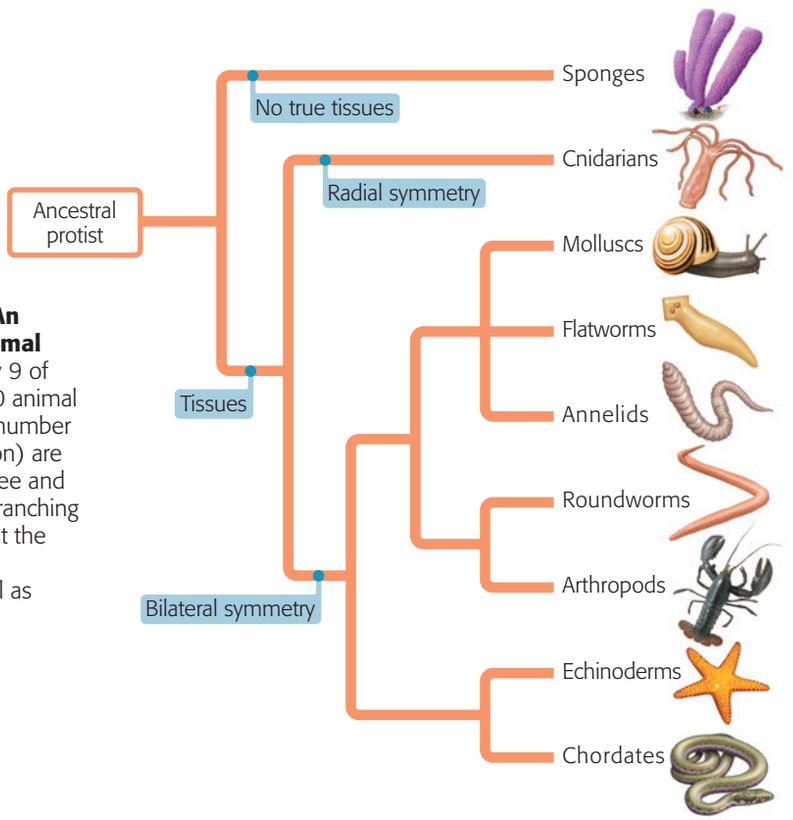
☑ CHECKPOINT

Why is animal evolution during the early Cambrian referred to as an "explosion"?

Answer: *because a great diversity of animals evolved in a relatively short time span*

Animal Phylogeny

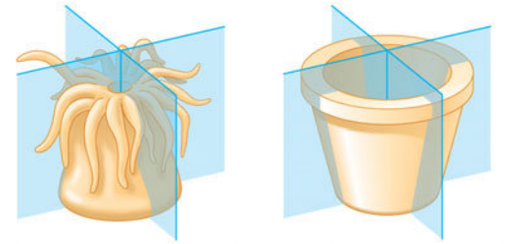
Historically, biologists have categorized animals by "body plan"—general features of body structure. Distinctions between body plans are used to help infer the evolutionary relationships between animal groups. More recently, a wealth of genetic data has allowed evolutionary biologists to modify and refine groups. **Figure 17.6** represents a set of hypotheses about the evolutionary relationships between nine major animal phyla based on structural and genetic similarities.



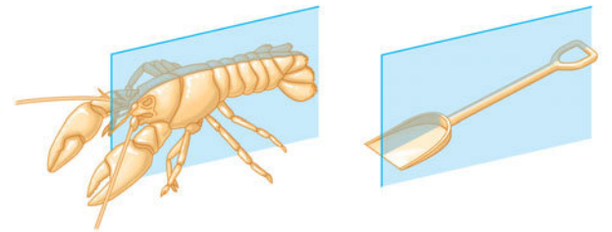
► **Figure 17.6 An overview of animal phylogeny.** Only 9 of the more than 30 animal phyla (the exact number is not agreed upon) are included in the tree and in the text. The branching takes into account the body plan of the organisms as well as genetic data.

A major branch point in animal evolution distinguishes sponges from all other animals based on structural complexity. Unlike more complex animals, sponges lack true tissues, groups of similar cells that perform a function (such as nervous tissue). A second major evolutionary split is based on body symmetry: radial versus bilateral **(Figure 17.7)**. To understand this difference, imagine a pail and shovel. The pail has **radial symmetry**, identical all around a central axis. The shovel has **bilateral symmetry**, which means there's only one way to split it into two equal halves—right down the midline. A bilateral animal has a definite "head end" that first encounters food, danger, and other stimuli when traveling. In most bilateral animals, a nerve center in the form of a brain is at the head end, near a concentration of sense organs such as eyes. Thus, bilateral symmetry is an adaptation that aids movement, such as crawling, burrowing, or swimming. Indeed, many radial animals are stationary, whereas most bilateral animals are mobile.

▼ **Figure 17.7 Body symmetry.**



Radial symmetry. Parts radiate from the center, so any slice through the central axis divides into mirror images.



Bilateral symmetry. Only one slice can divide left and right sides into mirror-image halves.

The evolution of body cavities also helped lead to more complex animals. A **body cavity** is a fluid-filled space separating the digestive tract from the outer body wall. The cavity enables the internal organs to grow and move independently of the outer body wall, and the fluid cushions them from injury. In soft-bodied animals such as earthworms, the fluid is under pressure and functions as a hydrostatic skeleton. Of the phyla shown in Figure 17.6, only sponges, cnidarians, and flatworms lack a body cavity.

Among animals with a body cavity, there are differences in how the cavity develops **(Figure 17.8)**. In all cases, the cavity is at least partly lined by a middle layer of tissue, called mesoderm, which develops between the inner (endoderm) and outer (ectoderm) layers of the gastrula embryo. If the body cavity is not completely lined by tissue derived from mesoderm, it is called a **pseudocoelom**. Among the animal phyla discussed in this chapter, only the roundworms (nematodes) have a pseudocoelom. A true **coelom**, the type of body cavity humans and many other animals have, is completely lined by tissue derived from mesoderm. (Despite its name, a pseudocoelom functions just like a coelom.)

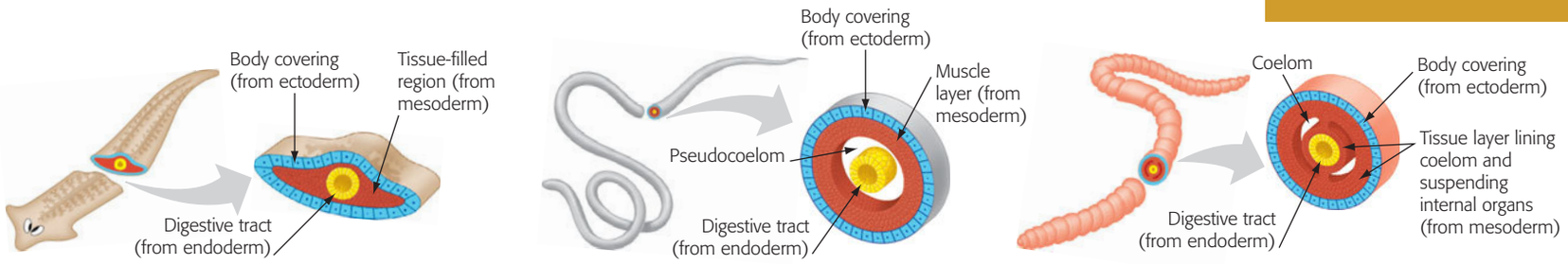
With the overview of animal evolution in Figure 17.6 as our guide, we're ready to take a closer look at the nine most numerous animal phyla. ☑

☑ CHECKPOINT

1. In terms of key body features, chordates are most like which other animal phylum?
2. A round pizza displays _____ symmetry, whereas a slice of pizza displays _____ symmetry.

Answers: **1.** *echinoderms* **2.** *radial; bilateral*

Figure 17.8 Body plans of bilateral animals. The various organ systems of these animals develop from the three tissue layers that form in the embryo.



(a) No body cavity: for example, flatworm

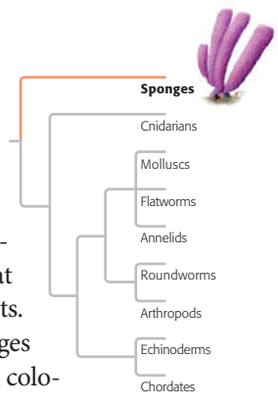
(b) Pseudocoelom: a body cavity only partially lined by the mesoderm, the middle tissue layer; for example, roundworm

(c) True coelom: a fluid-filled body cavity completely lined by mesoderm; for example, annelid

Major Invertebrate Phyla

Living as we do on land, our sense of animal diversity is biased in favor of vertebrates, animals with a backbone, such as amphibians, reptiles, and mammals. However, vertebrates make up less than 5% of all animal species. If we were to sample the animals in an aquatic habitat, such as a pond, tide pool, or coral reef, or if we were to consider the millions of insects that share our terrestrial world, we would find ourselves in the realm of **invertebrates**, animals without backbones. We give special attention to the vertebrates simply because we humans are among the backboned ones. However, by exploring the other 95% of the animal kingdom—the invertebrates—we'll discover an astonishing diversity of beautiful creatures that too often escape our notice.

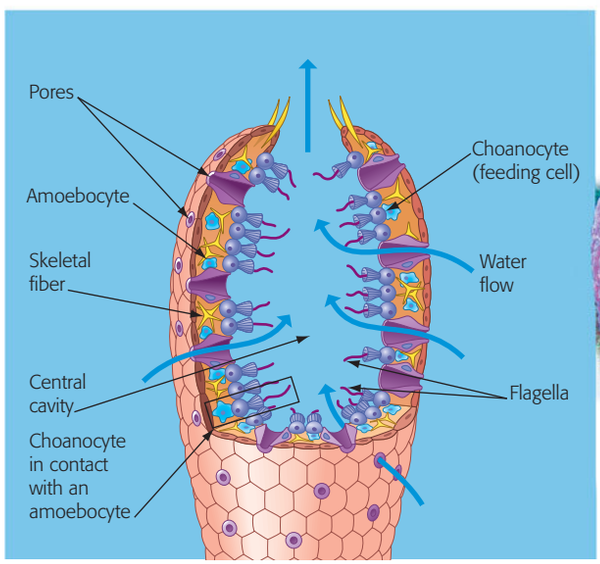
Sponges



Sponges were once grouped into the single phlyum Porifera. However, genetic evidence now suggests that there are multiple phyla. Sponges are stationary animals that appear so immobile that you might mistake them for plants. The simplest of all animals, sponges probably evolved very early from colonial protists. Sponges range in height from about 1 cm to 2 m. They have no nerves or muscles, but their individual cells can sense and react to changes in the environment. The cell layers of sponges are loose associations of relatively unspecialized cells that are not considered true tissues. Of the 9,000 or so species of sponges, only about 100 live in fresh water; the rest are marine.

The body of a sponge resembles a sac perforated with holes. Water is drawn through the pores into a central cavity and then flows out of the sponge through a larger opening (Figure 17.9). Cells called choanocytes have flagella that sweep water through the sponge's porous body. Choanocytes trap bacteria and other food particles in mucus and then engulf the food by endocytosis (see Figure 5.18). Cells called amoebocytes pick up food from the choanocytes, digest it, and carry the nutrients to other cells. Amoebocytes also manufacture the fibers that make up a sponge's skeleton. In some sponges, these fibers are sharp and spur-like. Other sponges have softer, more flexible skeletons; these pliant, honeycombed skeletons are often used as natural sponges in the bath or to wash cars. ☑

Figure 17.9 Anatomy of a sponge. To obtain enough food to grow by 3 ounces, a sponge must filter roughly 275 gallons of water through its body.



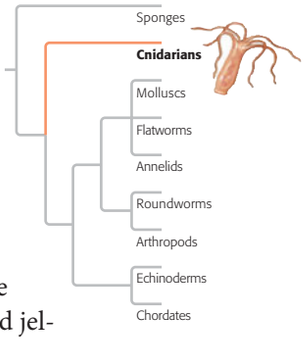


☑ CHECKPOINT

In what fundamental way does the structure of a sponge differ from that of all other animals?

Answer: A sponge has no true tissues.

Cnidarians



Cnidarians (phylum Cnidaria) are characterized by the presence of body tissues—as are all the remaining animals we will discuss—as well as by radial symmetry and tentacles with stinging cells. Cnidarians include sea anemones, hydras, corals, and jellies (sometimes called jellyfish, though they are not fish). Most of the 10,000 cnidarian species are marine.

The basic body plan of a cnidarian is a sac with a central digestive compartment, the **gastrovascular cavity**. A single opening to this cavity functions as both mouth and anus. This basic body plan has two variations: the stationary **polyp** and the floating **medusa** (Figure 17.10). Polyps adhere to larger objects and extend their tentacles, waiting for prey. Examples of the polyp body plan are hydras, sea anemones, and corals. A medusa (plural, *medusae*) is a flattened, mouth-down version of the polyp. It moves freely by a combination of passive drifting and contractions of its bell-shaped body. The largest jellies are medusae with tentacles 60–70 m long (more than half the length of a football field) dangling from an umbrella up to 2 m in diameter. There are some species of cnidarians that live only as polyps, others only as medusae, and still others that pass through both a medusa stage and a polyp stage in their life cycle.

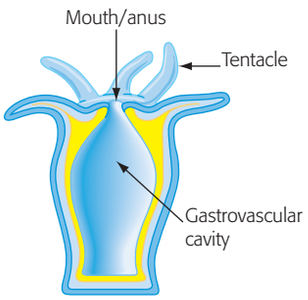
Cnidarians are carnivores that use tentacles arranged in a ring around the mouth to capture prey and push the food into the gastrovascular cavity, where digestion begins. The undigested remains are eliminated through the mouth/anus. The tentacles are armed with batteries of cnidocytes ("stinging cells") that function in defense and in the capture of prey (Figure 17.11). The phylum Cnidaria is named for these stinging cells. ☑

☑ CHECKPOINT

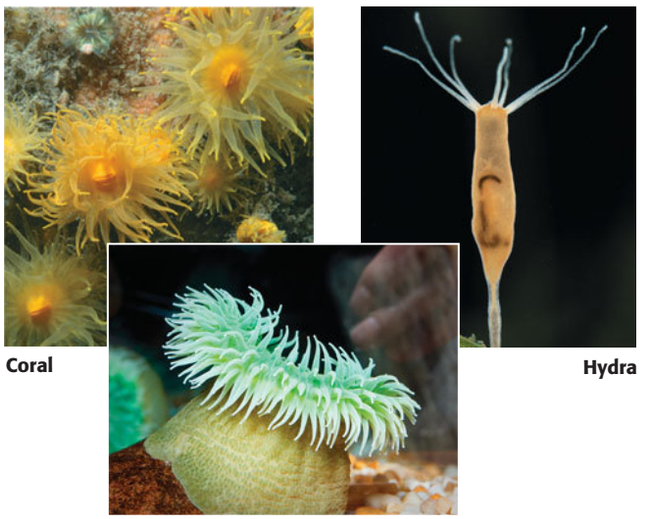
In what fundamental way does the body plan of a cnidarian differ from that of all other animals?

Answer: The body of a cnidarian is radially symmetric.

▼ Figure 17.10 Polyp and medusa forms of cnidarians. Note that cnidarians have two tissue layers, distinguished in the diagrams by blue and yellow. The gastrovascular cavity has only one opening, which functions as both mouth and anus.



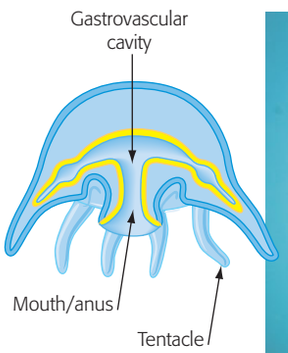
Polyp form



Coral

Hydra

Sea anemone

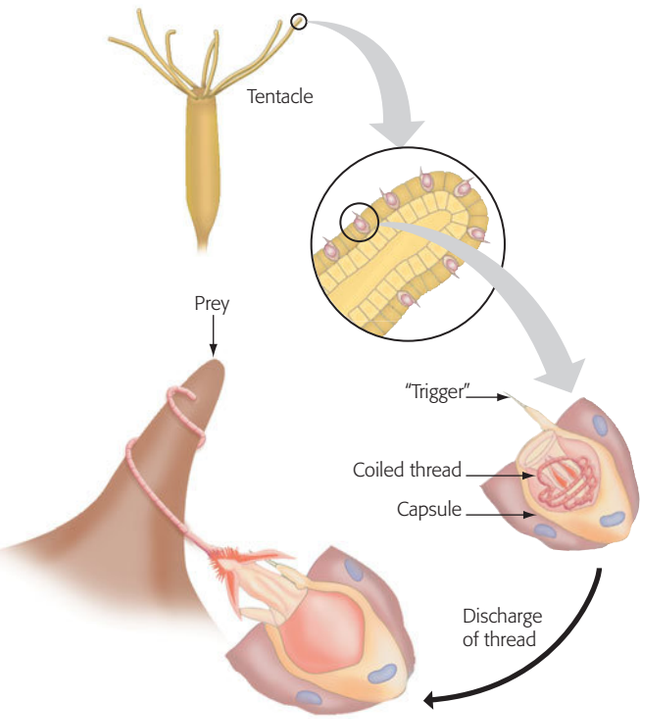


Medusa form



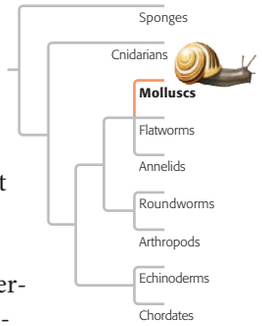
Jelly

▼ Figure 17.11 Cnidocyte action. When a trigger on a tentacle is stimulated by touch, a fine thread shoots out from a capsule. Some cnidocyte threads entangle prey, while others puncture the prey and inject a poison.



Cnidocyte

Molluscs



Snails and slugs, oysters and clams, and octopuses and squids are all **molluscs** (phylum Mollusca). Molluscs are soft-bodied animals, but most are protected by a hard shell. Slugs, squids, and octopuses have reduced shells, most of which are internal, or they have lost their shells completely during their evolution. Many molluscs feed by using a file-like organ called a **radula** to scrape up food. Garden snails use their radulas like tiny saws to cut pieces out of leaves.

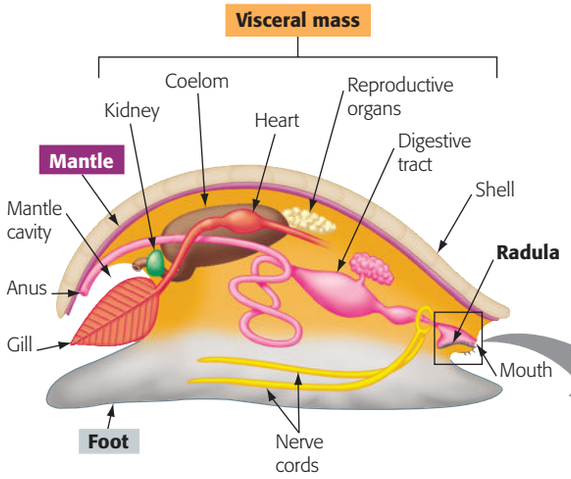
There are 93,000 known species of molluscs, with most being marine animals. All molluscs have a similar body plan **(Figure 17.12)**. The body has three main parts: a muscular foot, usually used for movement; a visceral mass containing most of the internal organs; and a fold of tissue called the mantle. The **mantle** drapes over the visceral mass and secretes the shell if one is present. The three major groups of molluscs are gastropods, bivalves, and cephalopods **(Figure 17.13)**.

Most **gastropods**, including snails, are protected by a single spiraled shell into which the animal can retreat when threatened. Slugs and sea slugs lack shells. Many gastropods have a distinct head with eyes at the tips of tentacles (think of a garden snail). Marine, freshwater, and terrestrial gastropods make up about three-quarters of the living mollusc species.

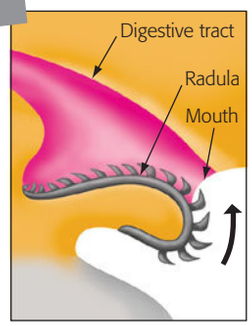
The **bivalves**, including clams, oysters, mussels, and scallops, have shells divided into two halves hinged together. None of the bivalves have a radula. There are both marine and freshwater species, with most being sedentary, using their muscular foot for digging and anchoring in sand or mud.

What do you call a squid that's even larger than a giant squid?

Cephalopods are all marine animals and generally differ from gastropods and sedentary bivalves in that their bodies are fast and agile. A few have large, heavy shells, but in most the shell is small and internal (as in squids) or missing (as in octopuses). Cephalopods have large brains and sophisticated sense organs, which contribute to their success as mobile predators. They use beak-like jaws and a radula to crush or rip prey apart. The mouth is at the base of the foot, which is drawn out into several long tentacles for catching and holding prey. The giant squid, which averages about 10 m in length, was thought to be the largest living invertebrate until an even larger species was discovered in the ocean depths near Antarctica. Scientists estimate that this massive cephalopod, dubbed the colossal squid, grows to an average length of 13 m—as long as a school bus. A specimen caught in 2007 weighed almost half a ton. ☑



◄ **Figure 17.12 The general body plan of a mollusc.** Note the body cavity (a true coelom, though a small one) and the complete digestive tract, with both mouth and anus.



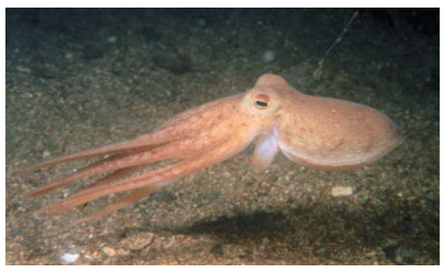
☑ CHECKPOINT

Classify these molluscs: A garden snail is an example of a _____; a clam is an example of a _____; a squid is an example of a _____.

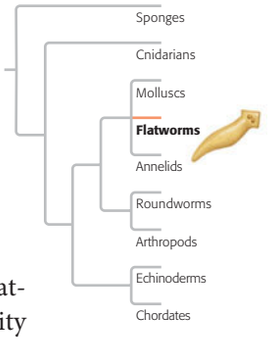
Answer: gastropod; bivalve; cephalopod

▼ **Figure 17.13 Mollusc diversity.**

MAJOR GROUPS OF MOLLUSCS

Gastropods	Bivalves (hinged shell)	Cephalopods (large brain and tentacles)	
 **Snail** (spiraled shell)	 **Scallop.** This scallop has many eyes (small round structures) peering out between the two halves of the hinged shell.	 **Octopus.** Octopuses live on the seafloor, where they search for crabs and other food. They have no shell. The brain of an octopus is larger and more complex, proportionate to body size, than that of any other invertebrate.	 **Nautilus.** The shell of the nautilus is a coiled series of chambers. The animal inhabits only the outermost chamber; the others contain gas and fluid that enable the nautilus to regulate its buoyancy.
 **Sea slug** (no shell)			

Flatworms



Flatworms (phylum Platyhelminthes) are the simplest animals with bilateral symmetry. True to their name, these worms are ribbonlike and range from about 1 mm to about 20 m (about 65 feet) in length. Most flatworms have a gastrovascular cavity with a single opening. There are about 20,000 species of flatworms living in marine, freshwater, and damp terrestrial habitats **(Figure 17.14)**.

The gastrovascular cavity of free-living flatworms called planarians is highly branched, providing an extensive surface area for the absorption of nutrients. When the animal feeds, a muscular tube projects through the mouth and sucks food in. Planarians live on the undersurfaces of rocks in freshwater ponds and streams.

Parasitic flatworms include blood flukes called schistosomes, which are a major health problem in the tropics. These worms have suckers that attach to the inside of the blood vessels near the human host's intestines. Infection by these flatworms causes a long-lasting disease called schistosomiasis or blood fluke disease, with such symptoms as severe abdominal pain, anemia, and dysentery. Although schistosomes are not found in the United States, more than 200 million people around the world are infected by these parasites each year.

Tapeworms parasitize many vertebrates, including people. Most tapeworms have a very long, ribbonlike body with repeated parts. There is no mouth and no gastrovascular cavity. The head of a tapeworm is armed with suckers and hooks that lock the worm to the intestinal lining of the host. Bathed in partially digested food in the intestines of its host, the tapeworm simply absorbs nutrients across its body surface. Behind the head is a long ribbon of units that are little more than sacs of sex organs. At the back of the worm, mature units containing thousands of eggs break off and leave the host's body with the feces. People can become infected with tapeworms by eating undercooked beef, pork, or fish containing tapeworm larvae. The larvae are microscopic, but the adults can reach lengths of 2 m in the intestine. Such large tapeworms can cause intestinal blockage and rob enough nutrients from the host to cause nutritional deficiencies. Fortunately, an orally administered drug can kill the adult worms. ☑

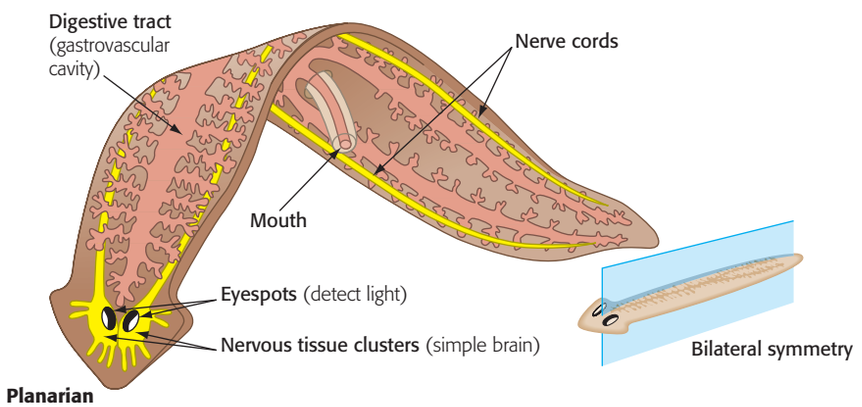
A tapeworm doesn't have a mouth, so how does it eat?

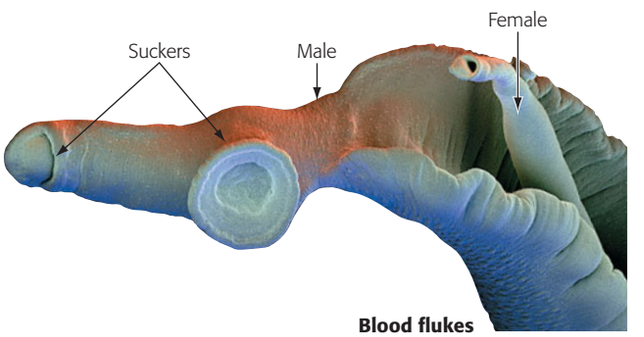
☑ CHECKPOINT

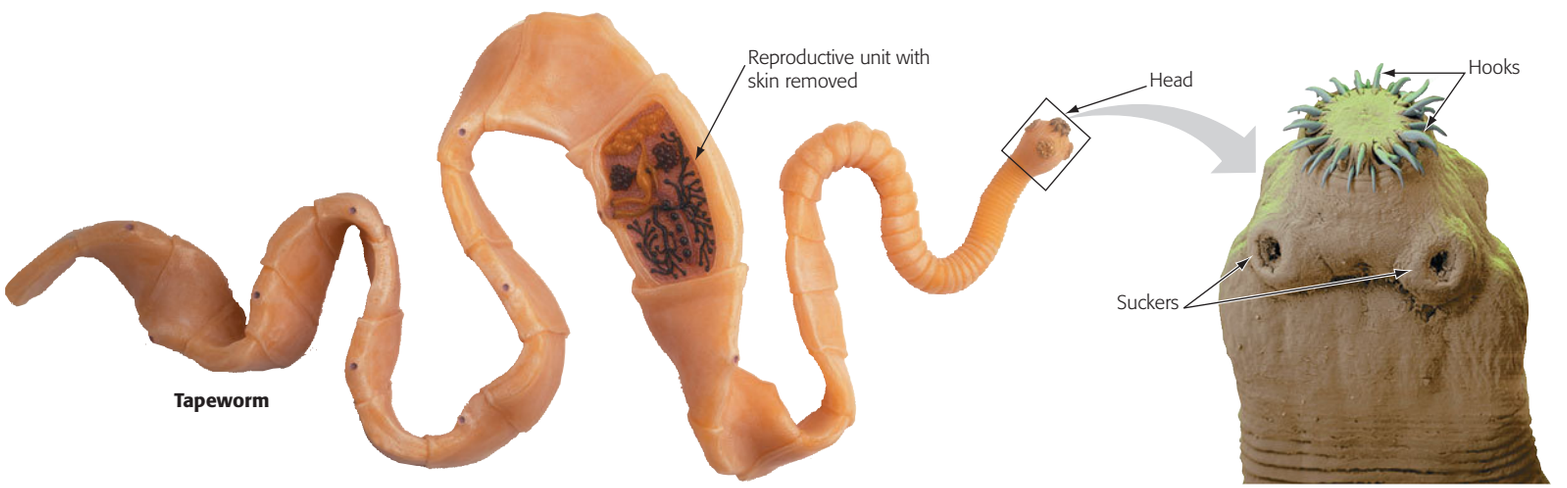
Flatworms are the simplest animals to display a body plan that is _____.

Answer: *bilaterally symmetric*

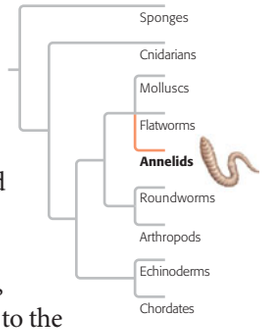
▼ Figure 17.14 Flatworm diversity.







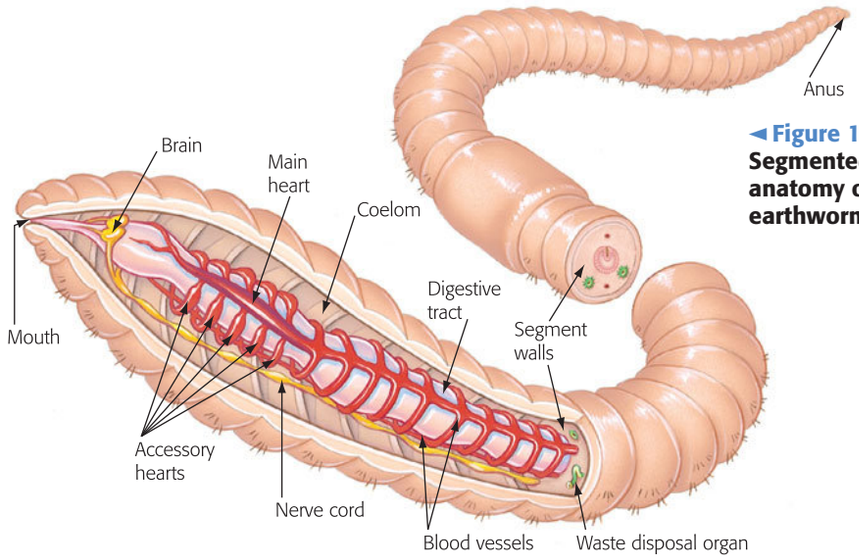
Annelids



Annelids (phylum Annelida) are worms that have **body segmentation**, which is the subdivision of the body along its length into a series of repeated parts called segments. In annelids, the segments look like a set of fused rings. There are about 16,000 annelid species, ranging in length from less than 1 mm to the 3-m giant Australian earthworm. Annelids live in damp soil, the sea, and most freshwater habitats. There are three main groups: earthworms, polychaetes, and leeches **(Figure 17.15)**.

Annelids exhibit two characteristics shared by all other bilateral animals except flatworms. One is a **complete digestive tract**, which is a digestive tube with two openings: a mouth and an anus. A complete digestive tract can process food and absorb nutrients as a meal moves in one direction from one specialized digestive organ to the next. In people, for example, the mouth, stomach, and intestines act as digestive organs. A second characteristic is a body cavity, which in this case is a coelom (a body cavity completely lined by mesoderm-derived tissue; see Figure 17.8c).

Earthworms, like all annelids, are segmented both externally and internally **(Figure 17.16)**. Many of the internal structures are repeated, segment by segment. The coelom (body cavity) is partitioned by walls (only two segment walls are fully shown here). The nervous system (yellow in the figure) and organs that dispose of fluid wastes (green) are repeated in each segment. The digestive tract, however, is not segmented; it passes through the segment walls from the mouth to the anus. Segmental blood vessels include one main heart and five pairs of accessory hearts.



◄ Figure 17.16 Segmented anatomy of an earthworm.

Earthworms eat their way through the soil, extracting nutrients as the soil passes through the digestive tract. Undigested material, mixed with mucus secreted into the digestive tract, is eliminated as castings through the anus. Farmers and gardeners value earthworms because the animals aerate the soil, and the castings improve the texture of the soil. Charles Darwin estimated that each acre of British farmland contained about 50,000 earthworms that produced 18 tons of castings per year.

▼ Figure 17.15 Annelid diversity.

MAJOR GROUPS OF ANNELIDS		
Earthworms	**Polychaetes**	**Leeches**
		
This giant Australian earthworm is bigger than many snakes. Perhaps you've slipped on slimy worms, but imagine actually tripping over one!	Polychaetes have segmental appendages that function in movement and as gills. This species is called a Christmas tree worm. The feathery, spiral structures are a pair of gills from a single worm.	The European freshwater leech *Hirudo medicinalis* can be used to repair tissue damage after reattachment surgery and other human trauma.

In contrast to earthworms, most **polychaetes** are marine, mainly crawling on or burrowing in the seafloor. Segmental appendages with hard bristles help the worm wriggle about in search of small invertebrates to eat. The appendages also increase the animal's surface area for taking up oxygen and disposing of metabolic wastes, including carbon dioxide.

✓ CHECKPOINT

The body plan of an annelid displays _____, meaning that the body is divided into a series of repeated regions.

Answer: *segmentation*

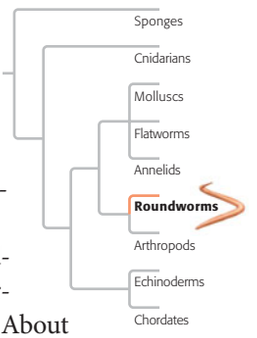
The third group of annelids, **leeches**, are notorious for the bloodsucking habits of some species. However, most species are free-living carnivores that eat small invertebrates such as snails and insects. A few terrestrial species inhabit moist vegetation in the tropics, but the majority of leeches live in fresh water. A European freshwater



Medicinal leech

species called *Hirudo medicinalis* is used for the treatment of circulatory complications. Most commonly, leeches are applied after reconstructive microsurgery in which limbs or digits are reattached. Because arteries (which transport blood into a reattached area) are easier to reconnect than veins (which transport blood out), blood can pool in the reattached area and stagnate, starving the healing tissue of oxygen. Medicinal leeches have razor-like jaws with hundreds of tiny teeth that cut through the skin. They secrete saliva containing an anesthetic and an anticoagulant into the wound. The anesthetic makes the bite virtually painless, and the anticoagulant prevents clotting as the leech drains excess blood from the wound. ✓

Roundworms



Roundworms (also called **nematodes**, members of the phylum Nematoda) get their common name from their cylindrical body, which is usually tapered at both ends **(Figure 17.17)**. Roundworms are among the most numerous and widespread of all animals. About 25,000 species of roundworms are known, and perhaps ten times that number actually exist. Roundworms range in length from about 1 mm to 1 m. They are found in most aquatic habitats, in wet soil, and as parasites in the body fluids and tissues of plants and animals.

✓ CHECKPOINT

Which phylum is most closely related to the roundworms? (*Hint*: Refer to the phylogenetic tree.)

Answer: *arthropods*

Free-living roundworms are important decomposers. They live virtually everywhere there is decaying organic matter, and their numbers are huge. Ninety thousand nematodes were found in a single rotting apple. In 2011, researchers even found nematodes living 2 miles underground, where they survive by grazing on microbes. Other species of nematodes thrive as parasites in plants and animals. Some are major agricultural pests that attack the roots of plants. At least 50 parasitic roundworm species infect people; they include pinworms, hookworms, and the parasite that causes trichinosis. ✓

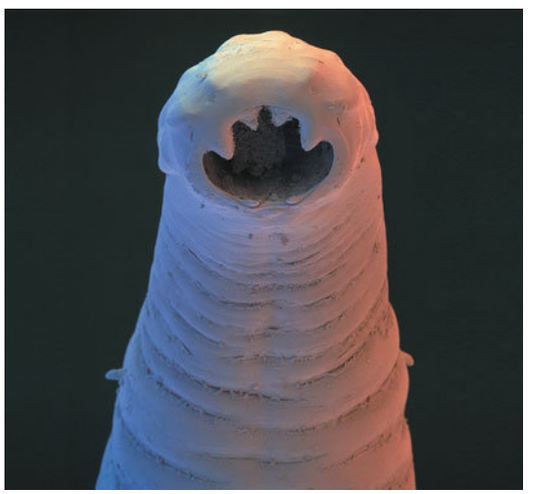
▼ Figure 17.17 Roundworm diversity.



(a) A free-living roundworm. This species has the classic roundworm shape: cylindrical with tapered ends. The ridges indicate muscles that run the length of the body.

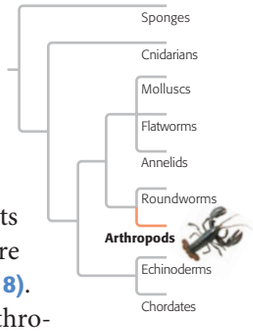


(b) Parasitic roundworms in pork. The potentially fatal disease trichinosis is caused by eating undercooked pork infected with *Trichinella* roundworms. The worms (shown here in pork tissue) burrow into a person's intestine and then invade muscle tissue.



(c) Head of hookworm. Hookworms sink their hooks into the wall of the host's small intestine and feed on blood. Although the worms are small (less than 1 cm), a severe infestation can cause serious anemia.

Arthropods

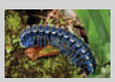


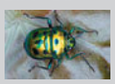
Arthropods (phylum Arthropoda) are named for their jointed appendages. Crustaceans (such as crabs and lobsters), arachnids (such as spiders and scorpions), and insects (such as grasshoppers and moths) are examples of arthropods **(Figure 17.18)**. Zoologists estimate that the total arthropod population numbers about a billion billion (10^{18}) individuals—that's about 150 million arthropods for each person! Researchers have identified over a million arthropod species, mostly insects. In fact, two out of every three species of life that have been scientifically described are arthropods. And arthropods are represented in nearly all habitats of the biosphere. In species diversity, distribution, and sheer numbers, arthropods must be regarded as the most successful animal phylum.

MAJOR GROUPS OF ARTHROPODS


Arachnids


Crustaceans


Millipedes and Centipedes


Insects

◄ Figure 17.18 Arthropod diversity.

General Characteristics of Arthropods

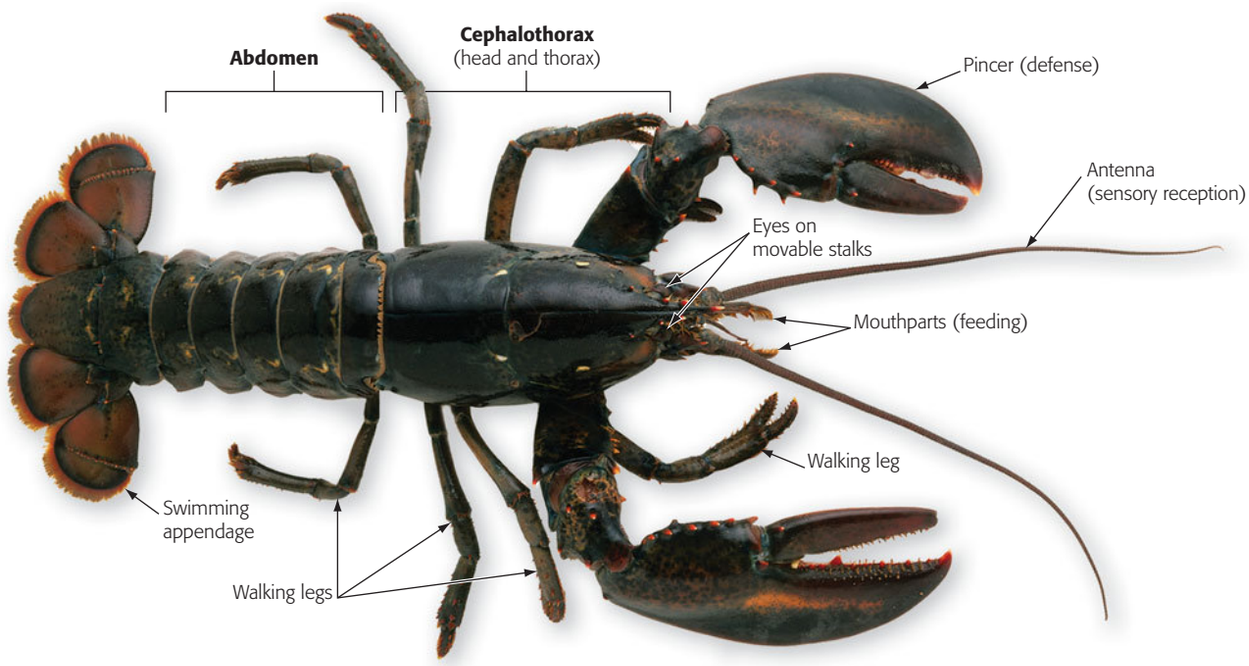
Arthropods are segmented animals. In contrast with the repeating similar segments of annelids, however, arthropod segments and their appendages have become specialized for a great variety of functions. This evolutionary flexibility contributed to the great diversification of arthropods. Specialization of segments (or of fused groups of segments) provides for an efficient division of labor among body regions. For example, the appendages of different segments may be adapted for walking, feeding, sensory reception, swimming, or defense **(Figure 17.19)**.

The body of an arthropod is completely covered by an **exoskeleton**, an external skeleton. This coat is constructed from layers of protein and a polysaccharide called chitin. The exoskeleton can be a thick, hard armor over some parts of the body (such as the head), yet be paper-thin and flexible in other locations (such as the joints). The exoskeleton protects the animal and provides points of attachment for the muscles that move the appendages. There are, of course, advantages to wearing hard parts on the outside. Our own skeleton is interior to most of our soft tissues, an arrangement that doesn't provide much protection from injury. But our skeleton does offer the advantage of being able to grow along with the rest of our body. In contrast, a growing arthropod must occasionally shed its old exoskeleton and secrete a larger one. This process, called molting, leaves the animal temporarily vulnerable to predators and other dangers. The next five pages explore the major groups of arthropods. ☑

☑ CHECKPOINT

What is the primary difference between your skeleton and a crab's skeleton?

Answer: Your skeleton is interior, whereas a crab has an exterior skeleton (an exoskeleton).



◄ Figure 17.19 Anatomy of a lobster, a crustacean. The whole body, including the appendages, is covered by an exoskeleton. The body is segmented, but this characteristic is obvious only in the abdomen.

Arachnids

Most **arachnids** live on land. Scorpions, spiders, ticks, and mites are examples **(Figure 17.20)**. Arachnids usually have four pairs of walking legs and a specialized pair of feeding appendages. In spiders, these feeding appendages are fang-like and equipped with poison glands. As a spider uses these appendages to immobilize and dismantle its prey, it spills digestive juices onto the torn tissues and sucks up its liquid meal.

▼ Figure 17.20 Arachnid characteristics and diversity.





Scorpion. Scorpions have a pair of large pincers that function in defense and food capture. The tip of the tail bears a poisonous stinger. Scorpions sting people only when prodded or stepped on.



Dust mite. This microscopic house dust mite is a ubiquitous scavenger in our homes. Dust mites are harmless except to people who are allergic to the mites' feces.



Spider. Like most spiders, including the tarantula in the large photo, this black widow spins a web of liquid silk, which solidifies as it comes out of specialized glands. A black widow's venom can kill small prey but is rarely fatal to humans.

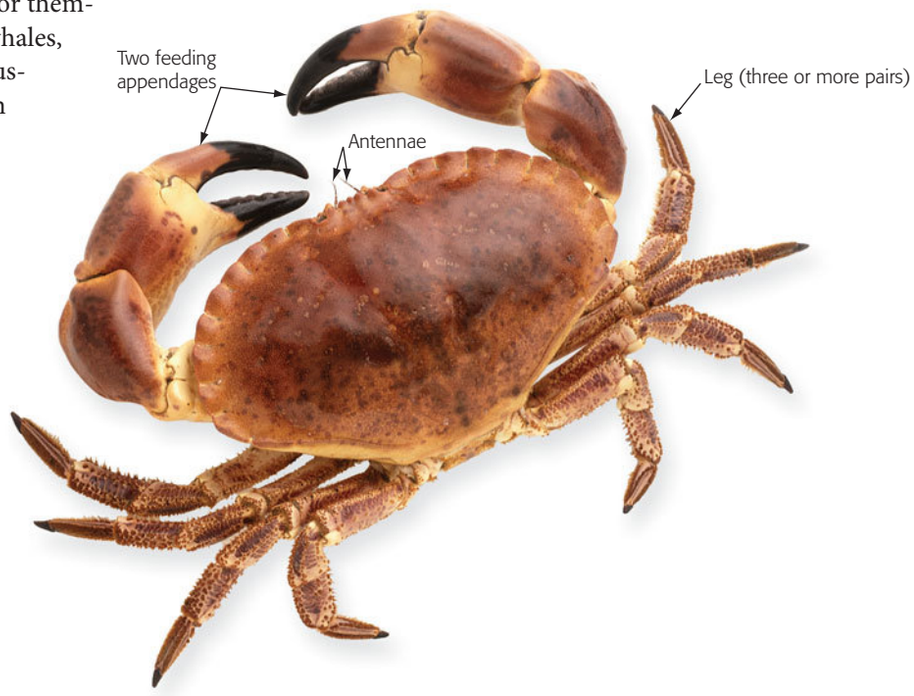


Wood tick. Wood ticks and other species carry bacteria that cause Rocky Mountain spotted fever. Lyme disease is carried by several different species of ticks.

Crustaceans

Crustaceans are nearly all aquatic, including delectable species of crabs, lobsters, crayfish, and shrimps **(Figure 17.21)**. Barnacles, which anchor themselves to rocks, boat hulls, and even whales, are also crustaceans. One group of crustaceans, the isopods, is represented on land by pill bugs. All of these animals exhibit the arthropod characteristic of multiple pairs of specialized appendages.

▼ Figure 17.21 Crustacean characteristics and diversity.





Crab. Ghost crabs are common along shorelines throughout the world. They scurry along the surf's edge and then quickly bury themselves in sand.



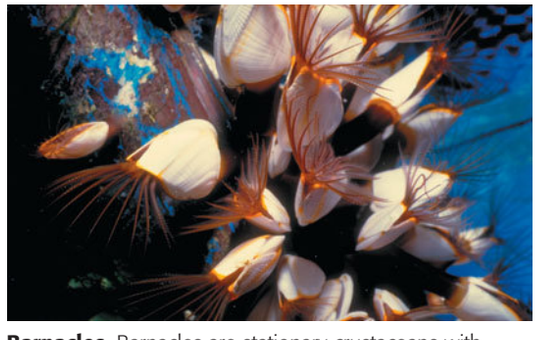
Shrimp. Naturally found in Pacific waters from Africa to Asia, giant prawns are widely cultivated as food.



Pill bug. Commonly found in moist locations with decaying leaves, such as under logs, pill bugs get their name from their tendency to roll up into a tight ball when they sense danger.



Crayfish. The red swamp crayfish, cultivated worldwide for food, becomes a pest when released outside of its native range in the southeastern United States.

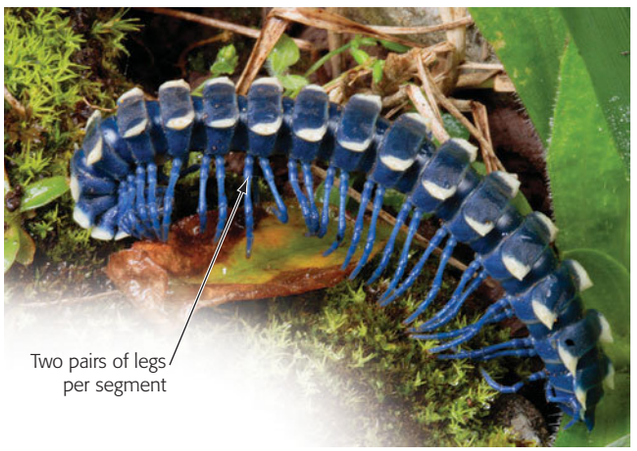


Barnacles. Barnacles are stationary crustaceans with exoskeletons hardened into shells by calcium carbonate (lime). The jointed appendages projecting from the shell capture small plankton.

Millipedes and Centipedes

Millipedes and **centipedes** have similar segments over most of the body and superficially resemble annelids, but their jointed legs reveal they are arthropods **(Figure 17.22)**. Millipedes are landlubbers that eat decaying plant matter. They have two pairs of short legs per body segment. Centipedes are terrestrial carnivores, with a pair of poison claws used in defense and to paralyze prey, such as cockroaches and flies. Each of their body segments bears a single pair of legs.

► **Figure 17.22 Millipedes and centipedes.**



Millipede. Like most millipedes, this blue millipede has an elongated body with two pairs of legs per trunk segment.



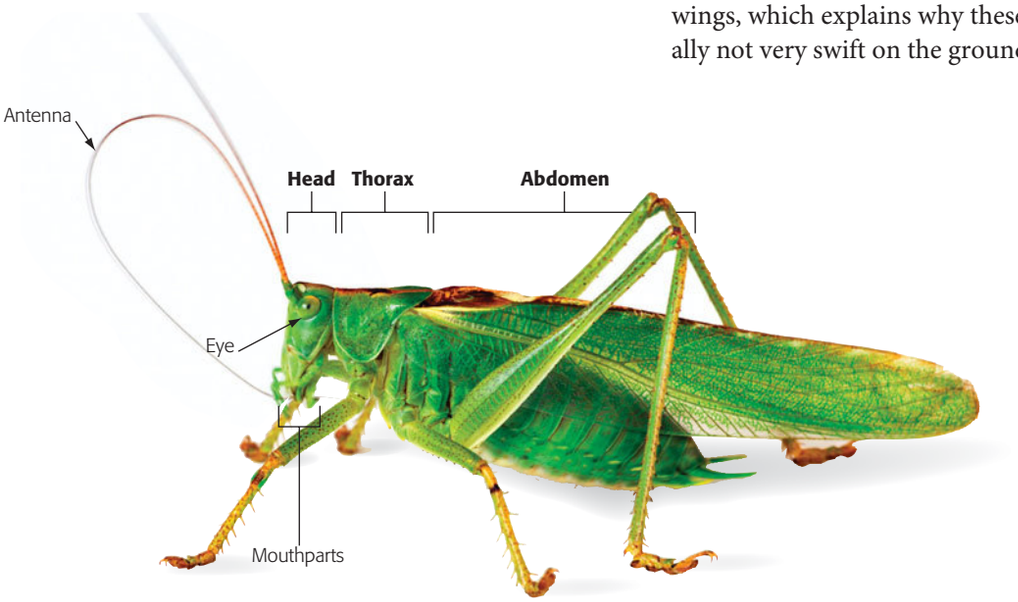
Centipede. Centipedes can be found in dirt and leaf litter. Their venomous claws can harm cockroaches and spiders, but not people.

Insect Anatomy

Like the grasshopper in **Figure 17.23**, most **insects** have a three-part body: head, thorax, and abdomen. The head usually bears a pair of sensory antennae and a pair of eyes. The mouthparts of insects are adapted for particular kinds of eating—for example, for biting and chewing plant material in grasshoppers; for lapping up fluids in houseflies; and for piercing skin and sucking blood in mosquitoes. Most adult insects have three pairs of legs and one or two pairs of wings, all extending from the thorax.

Flight is obviously one key to the great success of insects. An animal that can fly can escape many predators, find food and mates, and disperse to new habitats much faster than an animal that must crawl on the ground. Because their wings are extensions of the exoskeleton and not true appendages, insects can fly without sacrificing legs. By contrast, the flying vertebrates—birds and bats—have one of their two pairs of legs modified for wings, which explains why these vertebrates are generally not very swift on the ground.

▼ **Figure 17.23 Anatomy of a grasshopper.**



Insect Diversity

In species diversity, insects outnumber all other forms of life combined **(Figure 17.24)**. They live in almost every terrestrial habitat and in fresh water, and flying insects fill the air. Insects are rare in the seas, where crustaceans are the dominant arthropods. The oldest insect fossils date back to about 400 million years ago. Later, the evolution of flight sparked an explosion in insect variety.

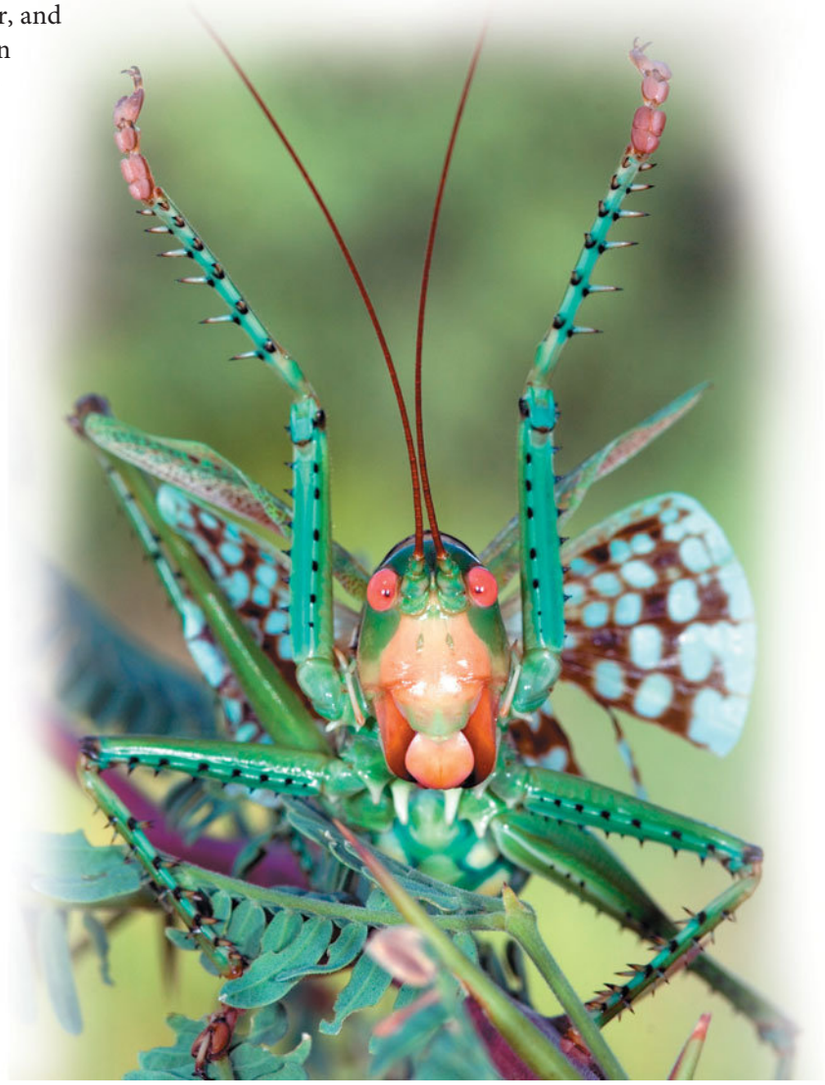
▼ Figure 17.24 Insect diversity.



Rhinoceros beetle. Only males have a "horn," which is used for fighting other males and for digging.



Red-and-black-striped stink bug. Members of this large insect family give off a foul-smelling liquid when disturbed.



Greater arid-land katydid. Often called the red-eyed devil, this scary-looking predator displays its wings and spiny legs when threatened.



Trilobite beetle. This beetle is found in the tropical rain forests of India and Southeast Asia.



Praying mantis. There are over 2,000 species of praying mantids throughout the world.



Jeweled beetle. Light reflected from varying thicknesses of chitin produces the brilliant colors of this beetle.



Buckeye butterfly. The eyespots on the wings of this butterfly may startle predators.



Rainbow bush locust. This colorful relative of grasshoppers is found in Madagascar.

Many insects undergo metamorphosis in their development. In the case of grasshoppers and some other insect groups, the young resemble adults but are smaller and have different body proportions. The animal goes through a series of molts, each time looking more like an adult, until it reaches full size. In other cases, insects have distinctive larval stages specialized for eating and growing that are known by such names as maggots (fly larvae), grubs (beetle larvae), or caterpillars (larvae of moths and butterflies). The larval stage looks entirely different from the adult stage, which is specialized for dispersal and reproduction. Metamorphosis from the larva to the adult occurs during a pupal stage **(Figure 17.25)**.

Forensic entomologists (forensic scientists who study insects) use their knowledge of insect life cycles to help solve criminal cases. For example, blowfly maggots feed on decaying flesh. Female blowflies, which can smell a dead body from up to a mile away, typically arrive and lay their eggs in a fresh corpse within minutes. By knowing the length of each stage in the life cycle of a blowfly, an entomologist can determine how much time has passed since death occurred.

When a killer dumps a body outdoors, who (or what) is first to arrive on the scene?

Animals so numerous, diverse, and widespread as insects are bound to affect the lives of all other terrestrial organisms, including people, in many ways. On the one hand, we depend on bees, flies, and other insects to pollinate our crops and orchards. On the other hand, insects are carriers of the microbes that cause many human diseases, such as malaria and West Nile disease. Insects also compete with people for food by eating our field crops. Trying to minimize their losses, farmers in the United States spend billions of dollars each year on pesticides, spraying crops with massive doses of insecticide poisons. But try as they might, not even humans have significantly challenged the preeminence of insects and their arthropod kin. As renowned entomologist Thomas Eisner put it: "Bugs are not going to inherit the Earth. They own it now. So we might as well make peace with the landlord." ☑

☑ CHECKPOINT

Which major arthropod group is mainly aquatic? Which is the most numerous?

Answer: crustaceans; insects

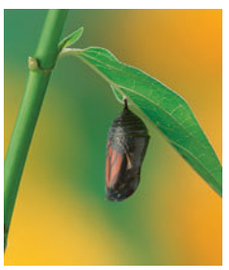
▼ Figure 17.25 Metamorphosis of a monarch butterfly.



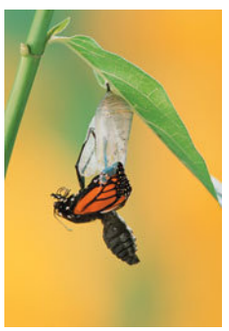
The **larva (caterpillar)** spends its time eating and growing, molting as it grows.



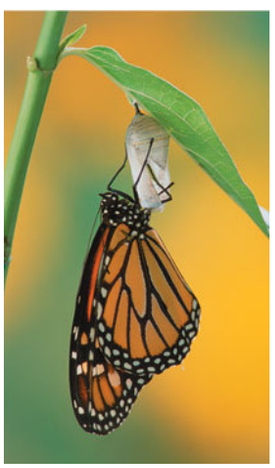
After several molts, the larva becomes a **pupa** encased in a cocoon.



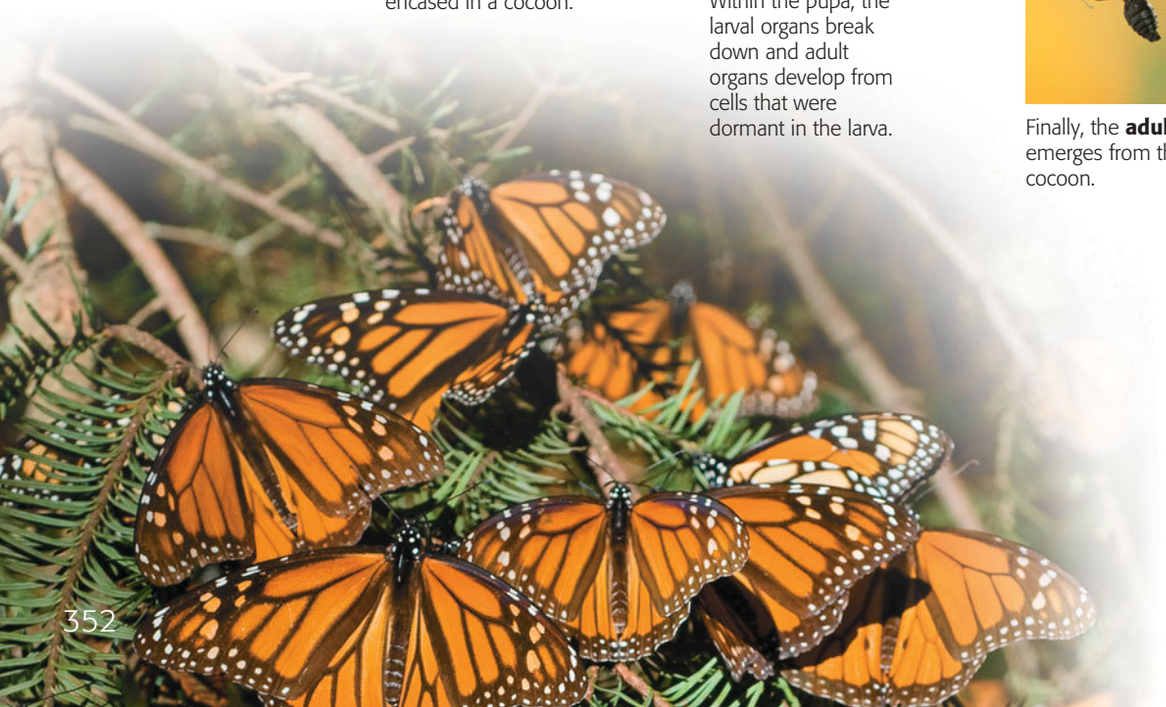
Within the pupa, the larval organs break down and adult organs develop from cells that were dormant in the larva.



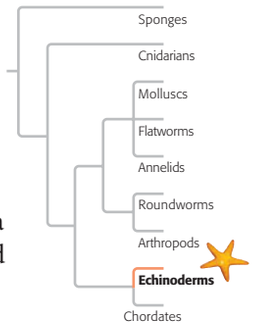
Finally, the **adult** emerges from the cocoon.



The butterfly flies off and reproduces, nourished mainly by calories stored when it was a caterpillar.



Echinoderms



The **echinoderms** (phylum Echinodermata) are named for their spiny surfaces (*echin* is Greek for "spiny"). Among the echinoderms are sea stars, sea urchins, sea cucumbers, and sand dollars **(Figure 17.26)**.

Echinoderms include about 7,000 species, all of them marine. Most move slowly, if at all. Echinoderms lack body segments, and most have radial symmetry as adults. Both the external and the internal parts of a sea star, for instance, radiate from the center like the spokes of a wheel. In contrast to the adult, the larval stage of echinoderms is bilaterally symmetric. This supports other evidence that echinoderms are not closely related to other radial animals, such as cnidarians, that never show bilateral symmetry. Most echinoderms have an **endoskeleton** (interior skeleton) constructed from hard plates just beneath the skin. Bumps and spines of this endoskeleton account for the animal's rough or prickly surface. Unique to echinoderms is the **water vascular system**, a network of water-filled canals that circulate water throughout the echinoderm's body, facilitating gas exchange (the entry of O_2 and the removal of CO_2) and waste disposal. The water vascular system also branches into extensions called tube feet. A sea star or sea urchin pulls itself slowly over the seafloor using its suction-cup-like tube feet. Sea stars also use their tube feet to grip prey during feeding.

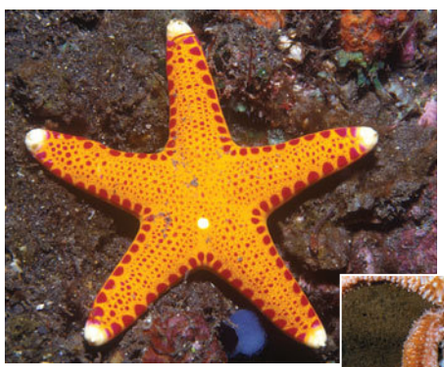
Looking at sea stars and other adult echinoderms, you may think they have little in common with humans and other vertebrates. But as shown by the phylogenetic tree at the left, echinoderms share an evolutionary branch with chordates, the phylum that includes vertebrates. Analysis of embryonic development can differentiate the echinoderms and chordates from the evolutionary branch that includes molluscs, flatworms, annelids, roundworms, and arthropods. With this context in mind, we're now ready to make the transition from invertebrates to vertebrates. ☑

☑ CHECKPOINT

Contrast the skeleton of an echinoderm with that of an arthropod.

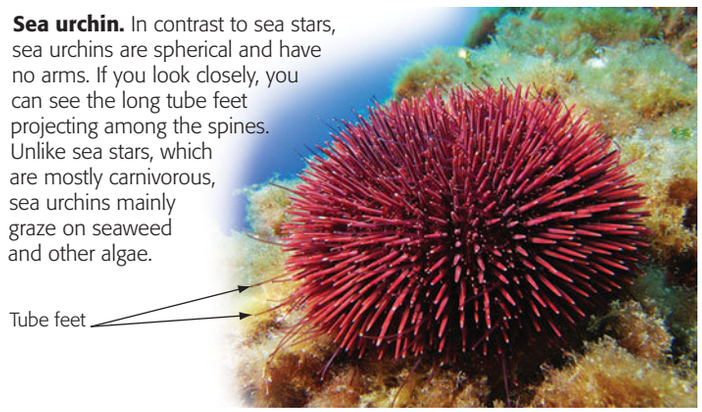
Answer: An echinoderm has an endoskeleton; an arthropod has an exoskeleton.

▼ Figure 17.26 Echinoderm diversity.

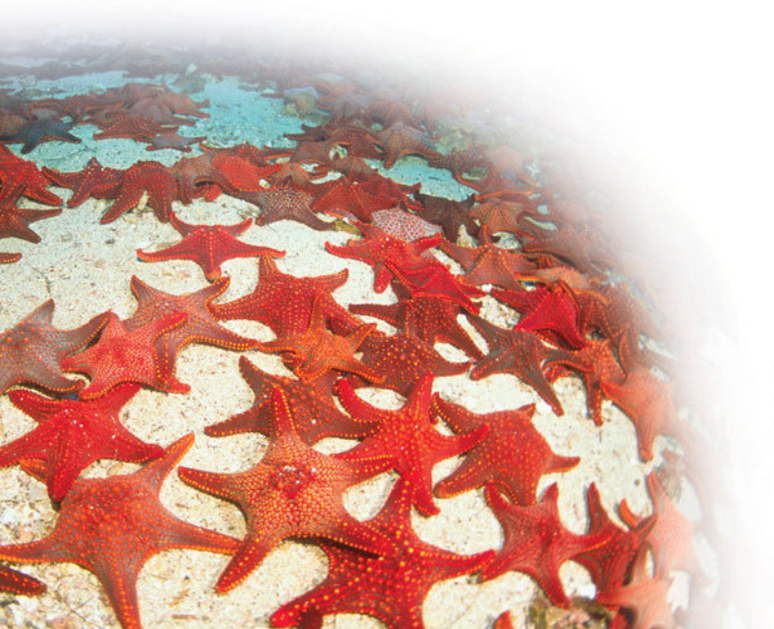




Sea star. When a sea star encounters an oyster or clam, it grips the mollusc's shell with its tube feet (see inset) and positions its mouth next to the narrow opening between the two halves of the prey's shell. The sea star then pushes its stomach out through its mouth and the crack in the mollusc's shell.



Sea urchin. In contrast to sea stars, sea urchins are spherical and have no arms. If you look closely, you can see the long tube feet projecting among the spines. Unlike sea stars, which are mostly carnivorous, sea urchins mainly graze on seaweed and other algae.





Sea cucumber. On casual inspection, this sea cucumber does not look much like other echinoderms. However, a closer look would reveal many echinoderm traits, including five rows of tube feet.

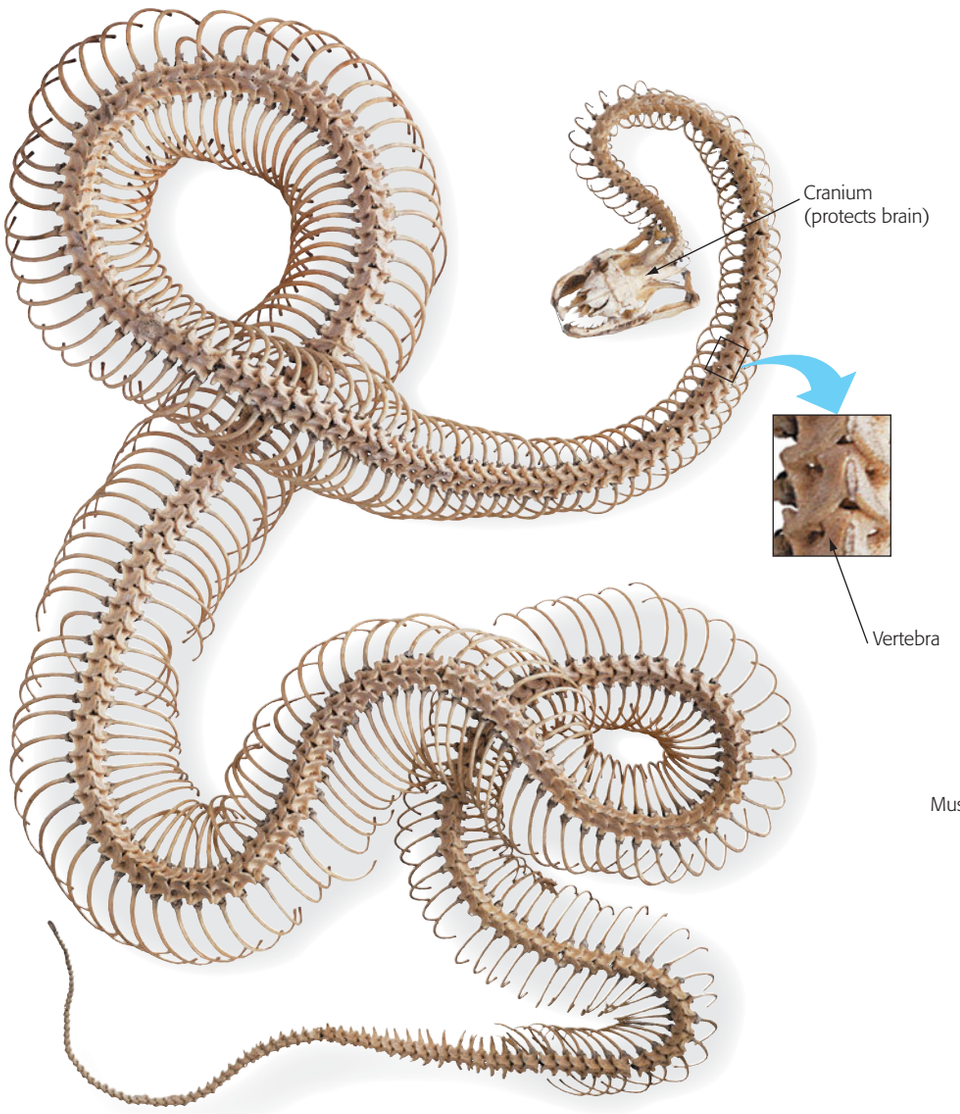


Sand dollar. Live sand dollars have a skin of movable spines covering a rigid skeleton. A set of five pores (arranged in a star pattern) allows seawater to be drawn into the sand dollar's body.

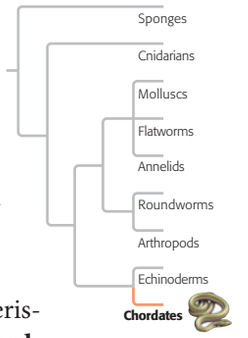
Vertebrate Evolution and Diversity

Most of us are curious about our family ancestry. Biologists are also interested in the larger question of tracing human ancestry within the animal kingdom. In this section, we trace the evolution of the vertebrates, the group that includes humans and their closest relatives. All vertebrates have endoskeletons, a characteristic shared with most echinoderms. However, vertebrate endoskeletons are unique in having a cranium (skull) and a backbone, a series of bones called vertebrae (singular, *vertebra*), for which the group is named **(Figure 17.27)**. Our first step in tracing the vertebrate lineage is to determine where vertebrates fit in the animal kingdom.

▼ Figure 17.27 A vertebrate endoskeleton. This snake skeleton, like those of all vertebrates, has a cranium (skull) and a backbone consisting of vertebrae.



Characteristics of Chordates

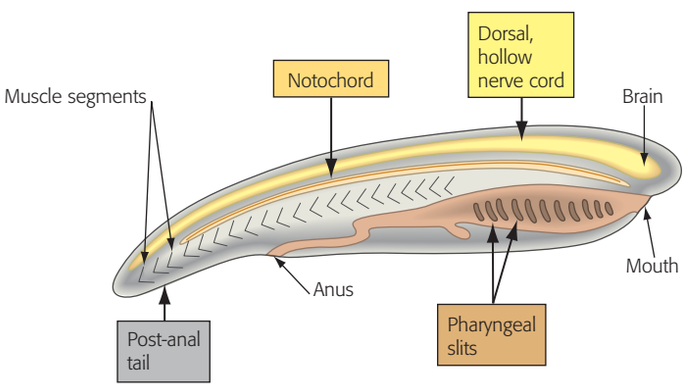


The last phylum in our survey of the animal kingdom is the phylum Chordata. **Chordates** share four key features that appear in the embryo and sometimes in the adult **(Figure 17.28)**. These four chordate characteristics are (1) a **dorsal, hollow nerve cord**; (2) a **notochord**, which is a flexible, longitudinal rod located between the digestive tract and the nerve cord; (3) **pharyngeal slits**, which are grooves in the pharynx, the region of the digestive tube just behind the mouth; and (4) a **post-anal tail**, which is a tail to the rear of the anus. Though these chordate characteristics are often difficult to recognize in the adult animal, they are always present in chordate embryos. For example, the notochord, for which our phylum is named, persists in adult humans only in the form of the cartilage disks that function as cushions between the vertebrae. Back injuries described as "ruptured disks" or "slipped disks" refer to these notochord remnants.

Body segmentation is another chordate characteristic. Chordate segmentation is apparent in the backbone of vertebrates (see Figure 17.27) and is also evident in the segmental muscles of all chordates (see the chevron-shaped—>>>>—muscles in the lancelet in Figure 17.29). Segmental musculature is not so obvious in adult humans unless one is motivated enough to sculpt those "washboard abs."

Three groups of chordates are invertebrates. Two of these groups, **tunicates** and **lancelets**, have no cranium **(Figure 17.29)**. The third group—hagfishes—have a cranium. (Hagfishes will be described shortly.) All other

▼ Figure 17.28 Chordate characteristics.



chordates are **vertebrates**, which retain the basic chordate characteristics but have additional features that are unique—including, of course, the backbone. **Figure 17.30** is an overview of chordate and vertebrate evolution that will provide a context for our survey. ☑

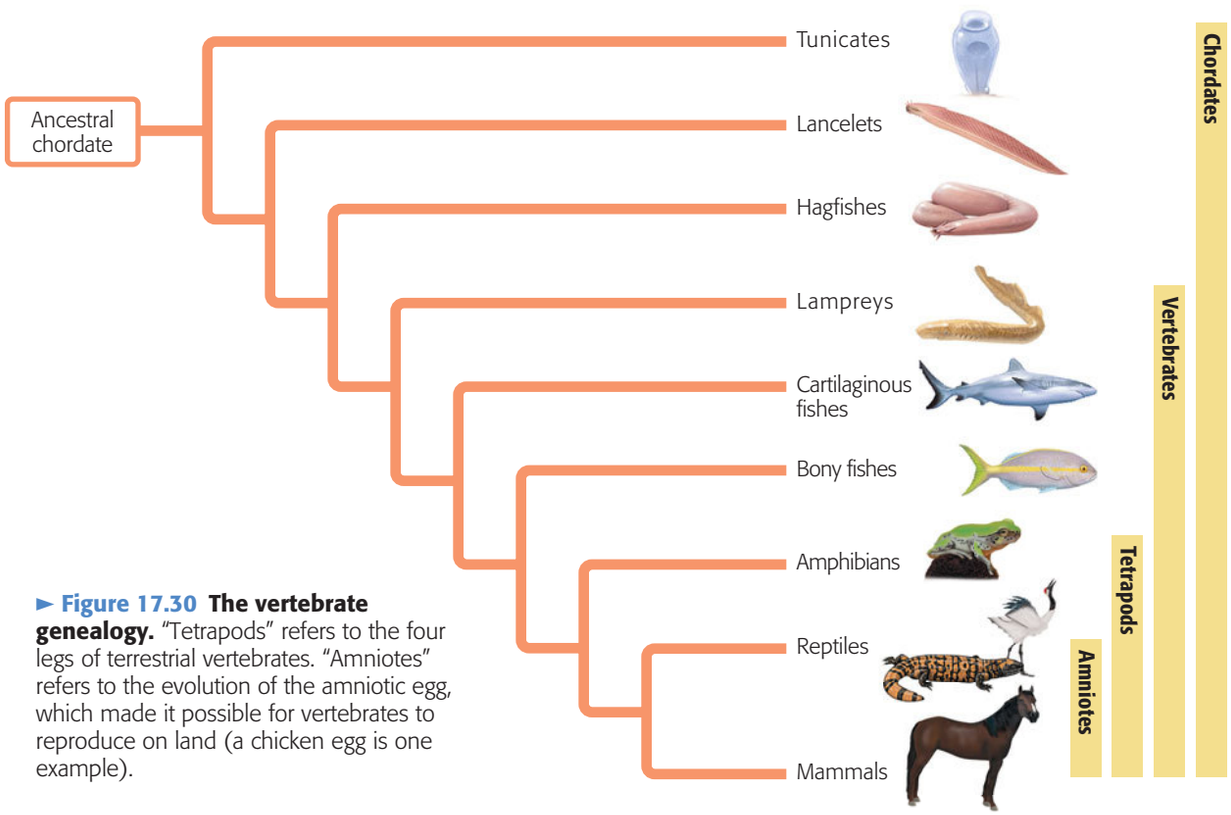
▼ Figure 17.29 Chordates that have no cranium or vertebrae.



Lancelet. This marine invertebrate owes its name to its bladelike shape. Only a few centimeters long, lancelets wiggle backward into the gravel, leaving their mouth exposed, and filter tiny food particles from the seawater.



Tunicates. The tunicate, or sea squirt, is a stationary animal that filters food from the water. These pastel sea squirts get their nickname from their coloration and the fact that they can quickly expel water to startle intruders.



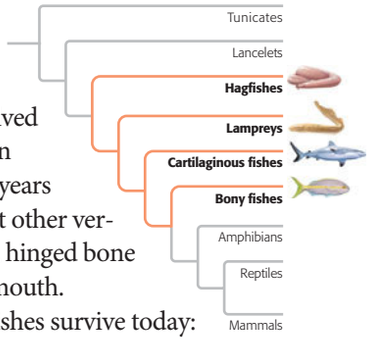
► Figure 17.30 The vertebrate genealogy. "Tetrapods" refers to the four legs of terrestrial vertebrates. "Amniotes" refers to the evolution of the amniotic egg, which made it possible for vertebrates to reproduce on land (a chicken egg is one example).

☑ CHECKPOINT

During our early embryonic development, what four features do we share with invertebrate chordates such as lancelets?

Answer: *(1) dorsal, hollow nerve cord; (2) notochord; (3) pharyngeal slits; (4) post-anal tail*

Fishes



The first vertebrates were aquatic and probably evolved during the early Cambrian period about 542 million years ago. In contrast with most other vertebrates, they lacked jaws, hinged bone structures that work the mouth.

Two types of jawless fishes survive today: hagfishes and lampreys. As noted earlier, hagfishes are invertebrates but have a cranium. Present-day hagfishes scavenge dead or dying animals on the cold, dark seafloor. When threatened, a hagfish exudes an enormous amount of slime from special glands on the sides of its body (Figure 17.31a). Recently, hagfishes have become endangered because their skin is used to make "eel-skin" belts, purses, and boots. Unlike hagfishes, lampreys are vertebrates. Some lampreys are parasites that use their jawless mouths as suckers to attach to the sides of large fish and draw blood (Figure 17.31b).

We know from the fossil record that the first jawed vertebrates were fishes that evolved about 470 million years ago. They had two pairs of fins, making them agile swimmers. Some early fishes were active predators up to 10 m in length that could chase prey and bite off chunks of flesh. Even today, most fishes are carnivores.

CHECKPOINT

A shark has a _____ skeleton, whereas a tuna has a _____ skeleton.

Answer: *cartilaginous; bony*

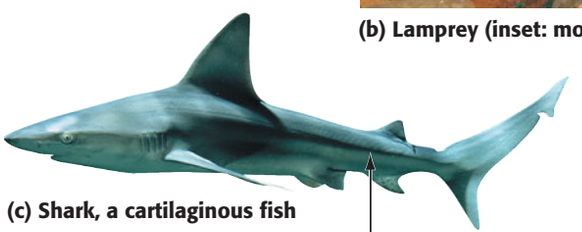
Figure 17.31 Fish diversity.



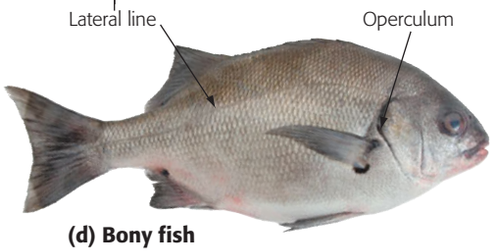
(a) Hagfish



(b) Lamprey (inset: mouth)



(c) Shark, a cartilaginous fish



(d) Bony fish

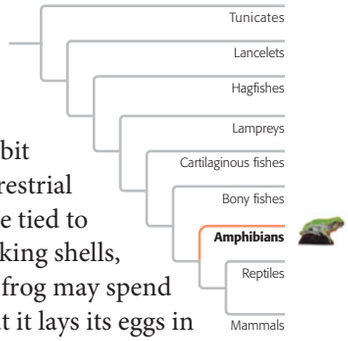
Cartilaginous fishes, such as sharks and rays, have a flexible skeleton made of cartilage (Figure 17.31c). Most sharks are adept predators because they are fast swimmers with streamlined bodies, acute senses, and powerful jaws. A shark does not have keen eyesight, but its sense of smell is very sharp. In addition, special electrosensors on the head can detect minute electrical fields produced by muscle contractions in nearby animals. Sharks also have a **lateral line system**, a row of sensory organs running along each side of the body. Sensitive to changes in water pressure, the lateral line system enables a shark to detect minor vibrations caused by animals swimming in its neighborhood. There are about 750 living species of cartilaginous fishes, nearly all of them marine.

The skeletons of **bony fishes** are reinforced by calcium (Figure 17.31d). Bony fishes have a lateral line system, a keen sense of smell, and excellent eyesight. On each side of the head, a protective flap called the **operculum** (plural, *opercula*) covers a chamber housing the gills, feathery external organs that extract oxygen from water. Movement of the operculum allows the fish to breathe without swimming. By contrast, sharks lack opercula and must swim to pass water over their gills. The need to move water over the gills is why a shark must keep moving to stay alive. Also unlike sharks, bony fishes have an organ that helps keep them buoyant—the **swim bladder**, a gas-filled sac. Thus, many bony fishes can conserve energy by remaining almost motionless, in contrast to sharks, which sink if they stop swimming. Some bony fishes have a connection between the swim bladder and the digestive tract that enables them to gulp air and extract oxygen from it when the oxygen level in the water gets too low.

Most bony fishes, including familiar species such as tuna, trout, and goldfish, are **ray-finned fishes**. Their fins are supported by thin, flexible skeletal rays. There are approximately 27,000 species of ray-finned fishes, the greatest number of species of any vertebrate group.

A second evolutionary branch includes the **lobe-finned fishes**. The lobe-fins are named for their muscular fins supported by stout bones that are homologous to amphibian limb bones. Early lobe-fins lived in coastal wetlands and may have used their fins to "walk" underwater. Today, three lineages of lobe-fins survive. The coelacanth is a deep-sea dweller once thought to be extinct. The lungfishes are represented by several Southern Hemisphere species that inhabit stagnant waters and gulp air into lungs connected to the pharynx. The third lineage of lobe-fins adapted to life on land and gave rise to amphibians, the first terrestrial vertebrates. ✓

Amphibians



In Greek, the word *amphibios* means "living a double life." Most **amphibians** exhibit a mixture of aquatic and terrestrial adaptations. Most species are tied to water because their eggs, lacking shells, dry out quickly in the air. A frog may spend much of its time on land, but it lays its eggs in water. An egg develops into a larva called a tadpole, a legless, aquatic algae-eater with gills, a lateral line system resembling that of fishes, and a long-finned tail. In changing into a frog, the tadpole undergoes a radical metamorphosis **(Figure 17.32a)**. When a young frog crawls onto shore and begins life as a terrestrial insect-eater, it has four legs, air-breathing lungs instead of gills, external eardrums, and no lateral line system. But even as adults, amphibians are most abundant in damp habitats, such as swamps and rain forests. This is partly because amphibians depend on their moist skin to supplement lung function in exchanging gases with the environment. Thus, even those frogs that are adapted to relatively dry habitats spend much of their time in humid burrows or under piles of moist leaves. The amphibians of today, including frogs and salamanders, account for about 12% of all living vertebrates, or about 6,000 species **(Figure 17.32b)**.

Amphibians were the first vertebrates to colonize land. They descended from fishes that had lungs and fins with muscles and skeletal supports strong enough to enable some movement, however clumsy, on land **(Figure 17.33)**. The fossil record chronicles the evolution of four-limbed amphibians from fishlike ancestors. Terrestrial vertebrates—amphibians, reptiles, and mammals—are collectively called **tetrapods**, which means "four feet." ☑

☑ CHECKPOINT

Amphibians were the first _____, four-footed terrestrial vertebrates.

Answer: tetrapods

▼ Figure 17.32 Amphibian diversity.





(a) Tadpole and adult gray tree frog



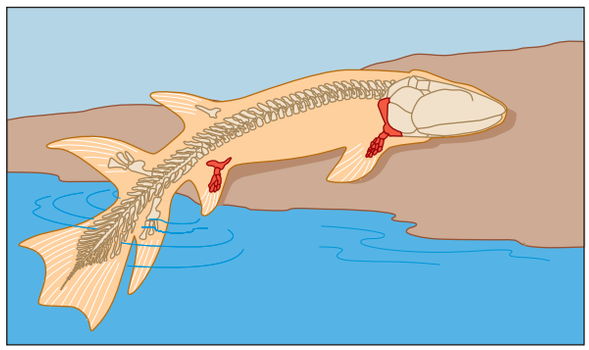
Malaysian horned frog



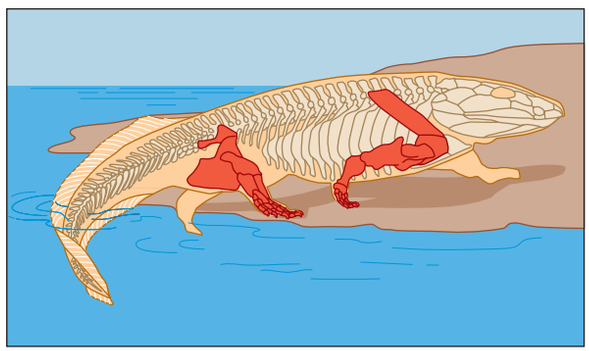
Texas barred tiger salamander

(b) Frogs and salamanders: the two major groups of amphibians

▼ Figure 17.33 The origin of tetrapods.

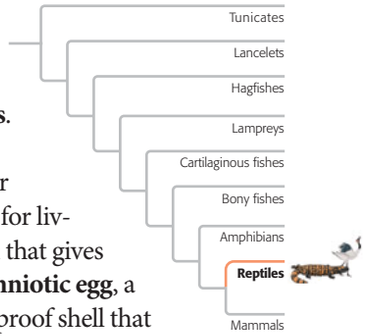


Lobe-finned fish. Fossils of some lobe-finned fishes have skeletal supports extending into their fins.



Early amphibian. Fossils of early amphibians have limb skeletons that probably functioned in helping them move on land.

Reptiles



Reptiles (including birds) and mammals are **amniotes**. The evolution of amniotes from an amphibian ancestor included many adaptations for living on land. The adaptation that gives the group its name is the **amniotic egg**, a fluid-filled egg with a waterproof shell that encloses the developing embryo. The amniotic egg functions as a self-contained "pond" that enables amniotes to complete their life cycle on land.

The **reptiles** include snakes, lizards, turtles, crocodiles, alligators, and birds, along with a number of extinct groups, including most of the dinosaurs **(Figure 17.34)**. The European grass snake in Figure 17.34 displays two reptilian adaptations to living on land: scaled waterproof skin, preventing dehydration in dry air, and amniotic eggs with shells, providing a watery, nutritious internal environment where the embryo can develop. These adaptations allowed reptiles to break their ancestral ties to aquatic habitats. Reptiles cannot breathe through their dry skin and so obtain most of their oxygen through their lungs.

Nonbird Reptiles

Nonbird reptiles are sometimes referred to as "cold-blooded" animals because they do not use their metabolism extensively to control body temperature. Reptiles do regulate body temperature, but largely through behavioral adaptations. For example, many lizards regulate their internal temperature by basking in the sun when the air is cool and seeking shade when the air is too warm. Because lizards and other nonbird reptiles absorb external heat rather than generating much of their own, they are said to be **ectotherms**, a term more accurate than "cold-blooded." By heating directly with solar energy rather than through the metabolic breakdown of food, a nonbird reptile can survive on less than 10% of the calories required by a mammal of equivalent size.

As successful as reptiles are today, they were far more widespread, numerous, and diverse during the Mesozoic era, which is sometimes known as the "age of reptiles." Reptiles diversified extensively during that era, producing a dynasty that lasted until about 65 million years ago. Dinosaurs, the most diverse reptile group, included the largest animals ever to inhabit land. Some were gentle giants that lumbered about while browsing vegetation. Others were voracious carnivores that chased their larger prey on two legs.

The age of reptiles began to fade about 70 million years ago. Around that time, the global climate became cooler and more variable. This was a period of mass extinctions that claimed all the dinosaurs by about 65 million years ago, except for one lineage (see Table 14.1). That lone surviving lineage is represented today by the reptilian group we know as birds. ✓

✓ CHECKPOINT

What is an amniotic egg?

Answer: a shelled egg surrounding fluid that contains an embryo

▼ Figure 17.34 Reptile diversity.



Snake. The shells of nonbird reptile eggs are leathery and flexible. This European grass snake is nonvenomous. When threatened, it may hiss and strike. If the bluff fails, it goes limp, pretending to be dead.



Turtle. The common box turtle, found throughout the eastern United States, can live for 100 years.



Lizard. The Gila monster, a desert-dweller of the Southwest, is the only venomous lizard native to the United States. Although large (up to 2 feet long), it moves too slowly to pose any danger to people.

Birds

Although **birds** were previously placed in their own class—class Aves—recent genetic and fossil evidence show that they are reptiles, having evolved from a lineage of small, two-legged dinosaurs called theropods. But today birds look quite different from reptiles because of their feathers and other distinctive flight equipment. Almost all of the 10,000 living bird species are airborne. The few flightless species, including the ostrich and the penguin, evolved from flying ancestors.

Where does the phrase "scarcer than hen's teeth" come from?

Appreciating the avian world is all about understanding flight. Almost every element of bird anatomy is modified in some way that enhances flight. The bones have a honeycombed structure that makes them strong but light. (The wings of airplanes have the same basic construction.) For example, a huge seagoing species called the frigate bird has a wingspan of more than 2 m (6.6 feet), but its whole skeleton weighs only about 113 g (a mere 4 ounces). Another adaptation that reduces the weight of birds is the absence of some internal organs found in other vertebrates. Female birds, for instance, have only one ovary instead of a pair. Also, today's birds are toothless, an adaptation that trims the weight of the head, preventing uncontrolled nosedives. Birds do not chew food in the mouth but grind it in the gizzard, a chamber of the digestive tract near the stomach.

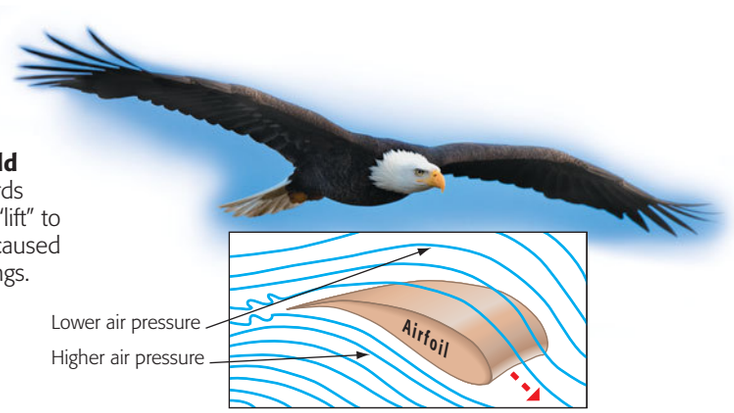
Flying requires a great expenditure of energy and an active metabolism. Unlike other reptiles, birds are **endotherms**, meaning they use their own metabolic heat to maintain a warm, constant body temperature.

A bird's most obvious flight equipment is its wings. Bird wings are airfoils that illustrate the same principles of aerodynamics as the wings of an airplane **(Figure 17.35)**. A bird's flight motors are its powerful breast muscles, which are anchored to a keel-like breastbone. It is mainly these flight muscles that we call "white meat" on chicken and turkey breasts. Some birds, such as eagles and hawks, have wings adapted for soaring on air currents and flap their wings only occasionally. Other birds, including hummingbirds, excel at maneuvering but must flap continuously to stay aloft. Feathers are made of the same protein that forms the scales of reptiles. Feathers may have functioned first as insulation, helping birds retain body heat, only later being adapted as flight gear. ☑

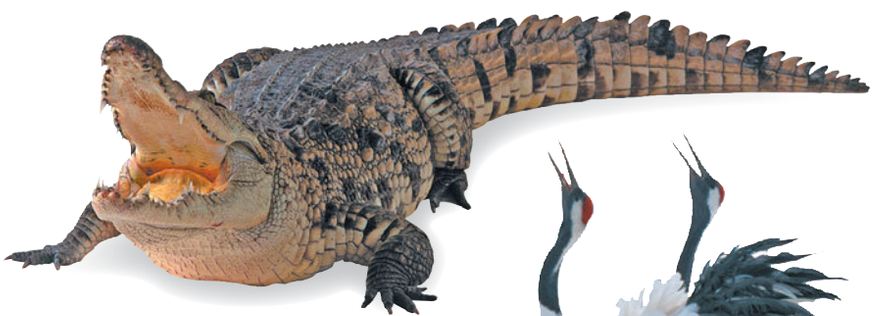
☑ CHECKPOINT

Birds differ from other reptiles in their main source of body heat, with birds being _____ and other reptiles being _____.

Answer: *endotherms; ectotherms*



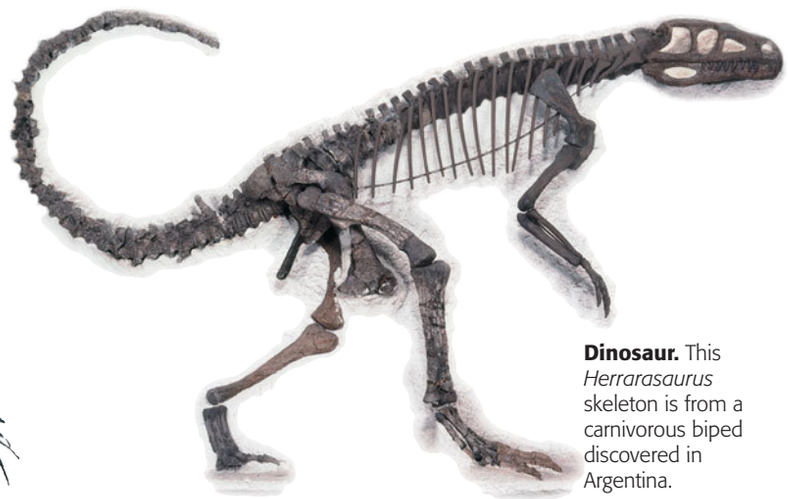
► **Figure 17.35 The aerodynamics of a bald eagle in flight.** Both birds and airplanes owe their "lift" to changes in air pressure caused by the shape of their wings.



Crocodile. Found throughout central and southern Africa, the Nile crocodile can grow up to 20 feet long and weigh nearly 2,000 pounds.

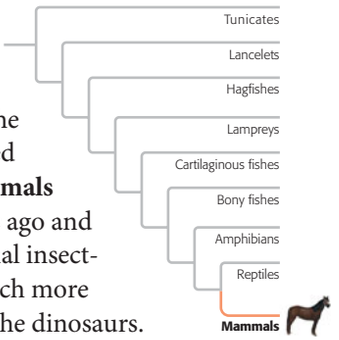


Birds. These red-crowned cranes, native to China, are performing an elaborate courtship dance.



Dinosaur. This *Herrarasaurus* skeleton is from a carnivorous biped discovered in Argentina.

Mammals



There are two major lineages of amniotes: one that led to the reptiles and one that produced the mammals. The first **mammals** arose about 200 million years ago and were probably small, nocturnal insect-eaters. Mammals became much more diverse after the downfall of the dinosaurs. Most mammals are terrestrial. These include nearly 1,000 species of winged mammals, the bats. And the roughly 80 species of dolphins, porpoises, and whales are totally aquatic. The blue whale—an endangered mammal that grows to lengths of nearly 30 m (about as long as a basketball court)—is the largest animal that has ever lived. Mammals have two unique characteristics: mammary glands (which produce milk that nourishes the young) and hair. The main function of hair is to insulate the body and help maintain a warm, constant internal temperature; like birds, mammals are endotherms.

The major groups of mammals are monotremes, marsupials, and eutherians **(Figure 17.36)**. The duck-billed platypus and the echidna, or spiny anteater, are the only existing species of **monotremes**, egg-laying mammals. The platypus lives along rivers in eastern Australia and on the nearby island of Tasmania. The female usually lays two eggs and incubates them in a leaf nest. After hatching, the young nurse by licking up milk secreted onto the mother's fur.

Most mammals are born rather than hatched. During pregnancy in marsupials and eutherians, the embryos are nurtured inside the mother by an organ called the **placenta**. Consisting of both embryonic and maternal tissues, the placenta joins the embryo to the mother within the uterus. The embryo receives oxygen and nutrients from maternal blood that flows close to the embryonic blood system in the placenta.

Marsupials, the so-called pouched mammals, include kangaroos, koalas, and opossums. These mammals have a brief pregnancy and give birth to tiny embryonic offspring that complete development while attached to the mother's nipples. The nursing young of most marsupials are housed in an external pouch on the mother's abdomen. Nearly all marsupials live in Australia, New Zealand, and North and South America. Australia has been a marsupial sanctuary for much of the past 60 million years. Australian marsupials have diversified extensively, filling terrestrial habitats that on the other continents are occupied by eutherian mammals.

Eutherians are also called **placental mammals** because their placentas provide a more intimate and longer-lasting association between the mother and her developing young than do marsupial placentas. Eutherians make up almost 95% of the 5,300 species of living mammals. Dogs, cats, cows, rodents, rabbits, bats, and whales are all examples of eutherian mammals. One of the eutherian groups is the primates, which include monkeys, apes, and humans. ☑

☑ CHECKPOINT

What are two defining characteristics of mammals?

Answer: mammary glands and hair

▼ Figure 17.36 Mammalian diversity.

MAJOR GROUPS OF MAMMALS

Monotremes (hatched from eggs)	**Marsupials** (embryonic at birth)	**Eutherians** (fully developed at birth)
		
Monotremes, such as this duck-billed platypus, are the only mammals that lay eggs. Like other mammals, platypus mothers nourish their young with milk.	The young of marsupials are born very early in their development. The newborn kangaroo will finish its growth while nursing from a nipple in its mother's pouch.	In eutherians (placental mammals), young develop within the uterus of the mother. There they are nurtured by the flow of blood through the dense network of vessels in the placenta. This newborn foal is coated by remnants of the placenta.

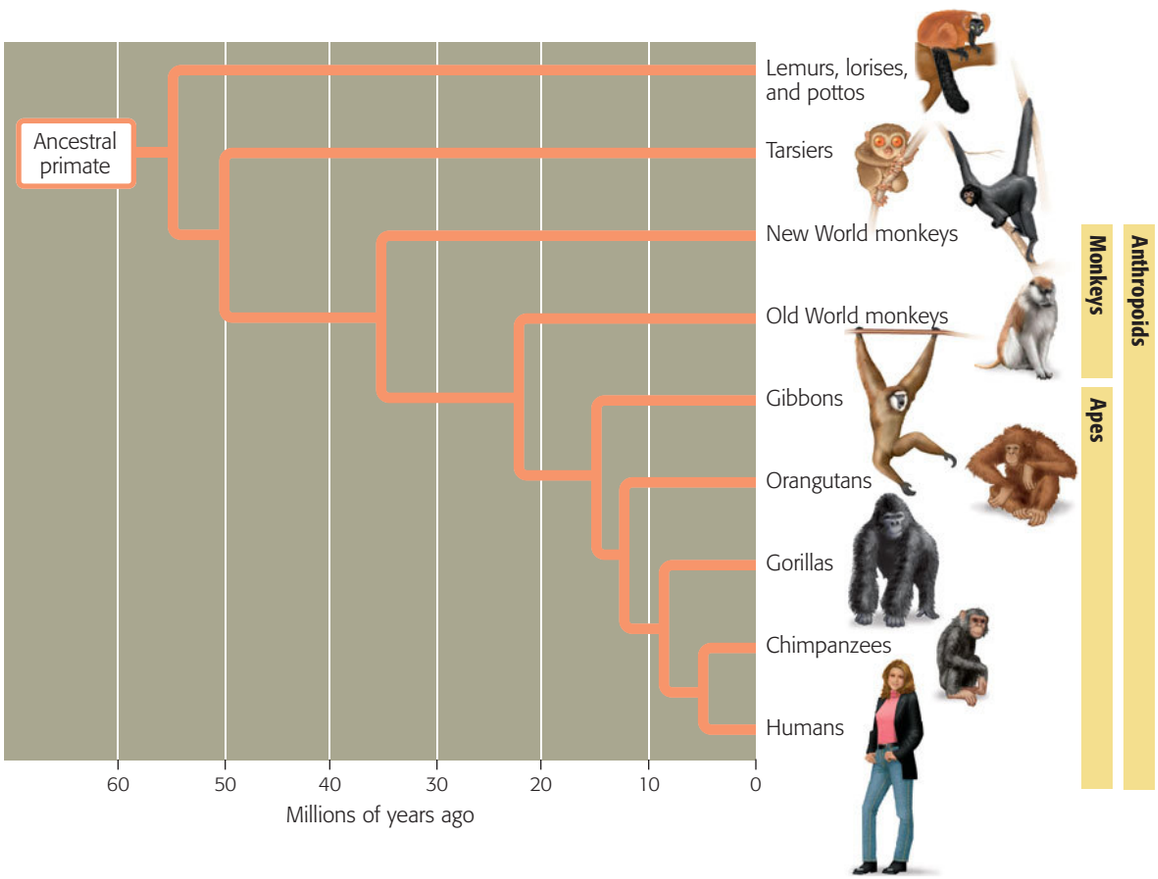
The Human Ancestry

We have now traced animal phylogeny to the **primates**, the mammalian group that includes us—*Homo sapiens*—and our closest kin. To understand what that means, we must follow our ancestry back to the trees, where some of our most treasured traits originated.

The Evolution of Primates

Primate evolution provides a context for understanding human origins. The fossil record supports the hypothesis that primates evolved from insect-eating mammals during the late Cretaceous period, about 65 million years ago. Those early primates were small, arboreal (tree-dwelling) mammals. Thus, primates were first distinguished by characteristics that were shaped, through natural selection, by the demands of living in the trees. For example, primates have limber shoulder joints, which make it possible to swing from branch to branch. The agile hands of primates can hang on to branches and manipulate food. Nails have replaced claws in many primate species, and the fingertips are very sensitive. The eyes of primates are close together on the front of the face. The overlapping fields of vision of the two eyes enhance depth perception, an obvious advantage when swinging in trees. Excellent eye-hand coordination is also important for arboreal maneuvering. Parental care is essential for young animals in the trees. Mammals devote more energy to caring for their young than most other vertebrates, and primates are among the most attentive parents of all mammals. Most primates have single births and nurture their offspring for a long time. Although humans never lived in trees, we retain in modified form many traits that originated there.

Taxonomists divide the primates into three main groups **(Figure 17.37)**. The first includes lemurs, lorises, and pottos. These primates live in Madagascar, southern Asia, and Africa. Tarsiers, small nocturnal tree-dwellers found only in Southeast Asia, form the second group of primates. The third group of primates, **anthropoids**, includes monkeys and apes. All monkeys in the New World (the Americas) are arboreal and are distinguished by prehensile (grasping) tails that function as an extra appendage for swinging. If you see a monkey in a zoo swinging by its tail, you know it's from the New World. Although some Old World (African and Asian) monkeys are also arboreal, their tails are not prehensile. And many Old World monkeys, including baboons, macaques, and mandrills,



◄ **Figure 17.37** **Primate phylogeny.**

are mainly ground-dwellers. Anthropoids also have a fully opposable thumb; that is, they can touch the tips of all four fingers with their thumb.

What's the difference between apes and monkeys?

Our closest anthropoid relatives are the nonhuman apes: gibbons, orangutans, gorillas, and chimpanzees. They live only in tropical regions of the Old World. Except for some gibbons, apes are larger than monkeys, with relatively long arms, short legs, and no tail. Although all apes are capable of living in trees, only gibbons and orangutans are primarily arboreal. Gorillas and chimpanzees are highly social. Apes have larger brains proportionate to body size than monkeys, and their behavior is more adaptable. And, of course, the apes include humans. **Figure 17.38** shows examples of primates.

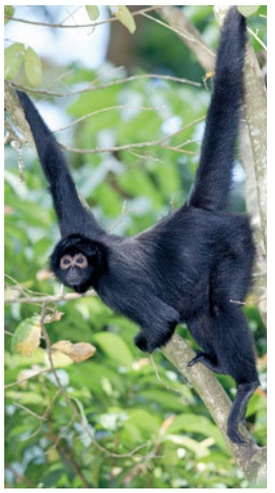
▼ Figure 17.38 Primate diversity.



Red ruffed lemur



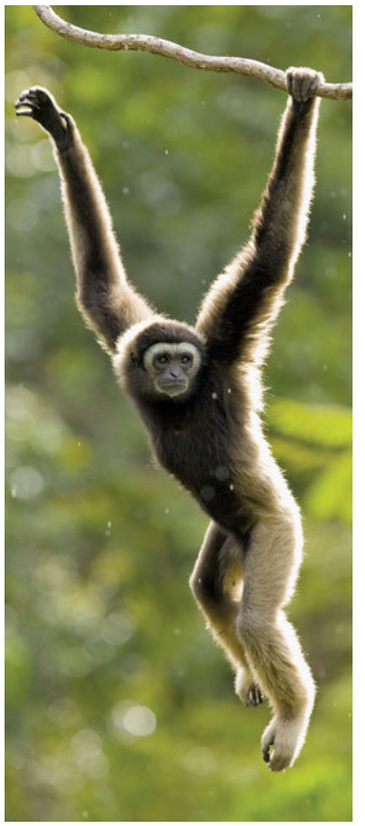
Tarsier



Black spider monkey (New World monkey)



Patas monkey (Old World monkey)



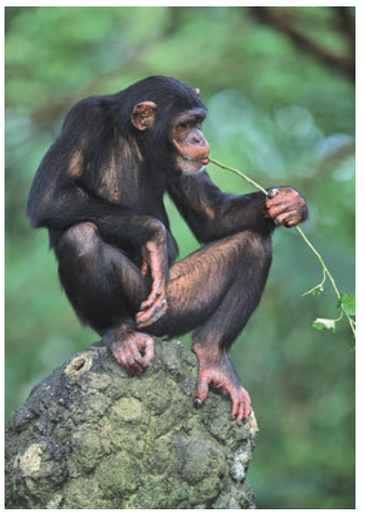
Gibbon (ape)



Orangutan (ape)



Gorilla (ape)



Chimpanzee (ape)



Human

The Emergence of Humankind

Humanity is one very young twig on the tree of life. In the continuum of life spanning 3.5 billion years, the fossil record and molecular systematics indicate that humans and chimpanzees have shared a common African ancestry for all but the last 5–7 million years (see Figure 17.37). Put another way, if we compressed the history of life to a year, the human branch has existed for only 18 hours.

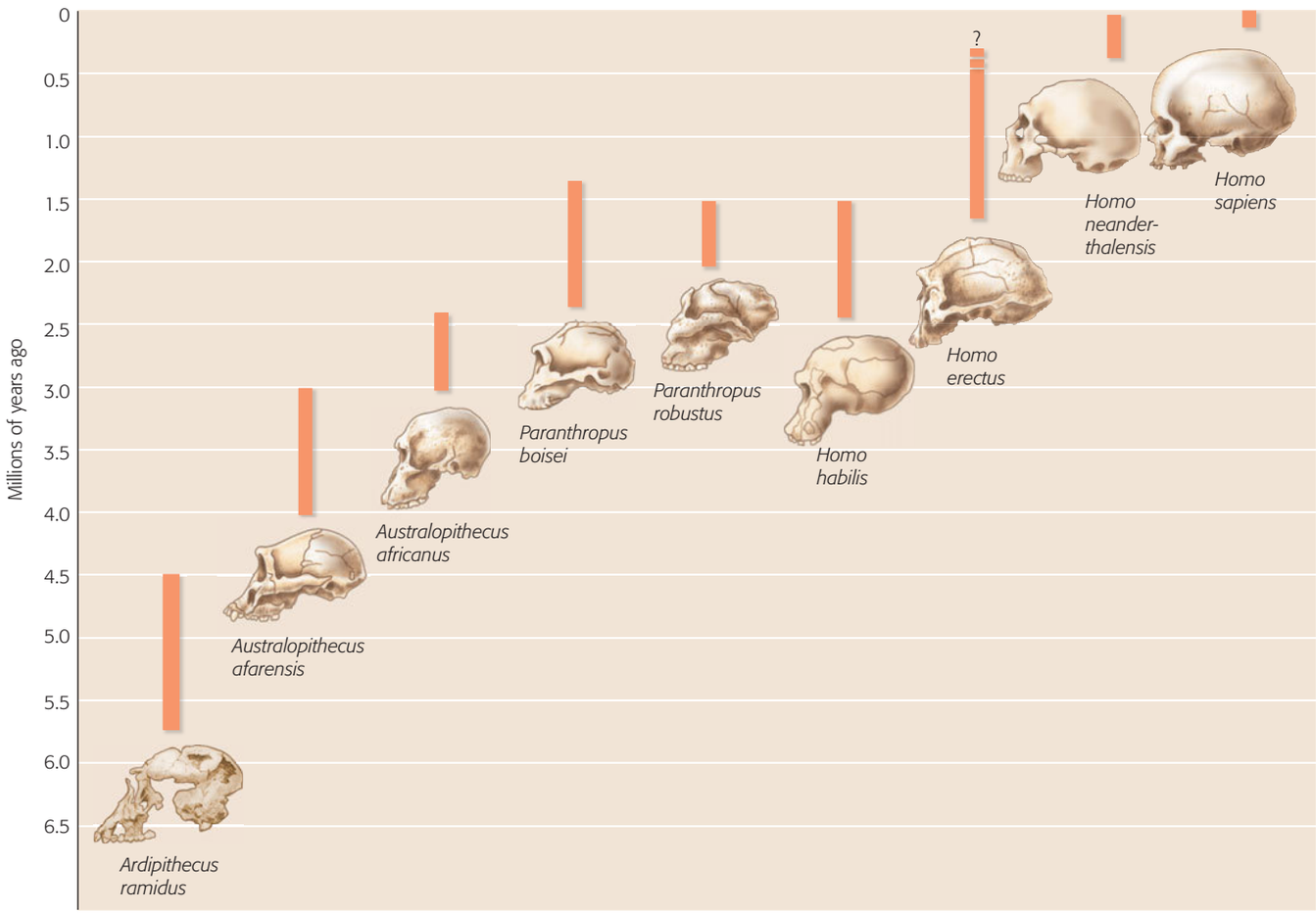
Some Common Misconceptions

Certain misconceptions about human evolution persist in the minds of many, long after these myths have been debunked by the fossil evidence. Let's first dispose of the myth that our ancestors were chimpanzees or any other modern ape. Although 5–7 million years is a brief time span relative to the 3.5-billion-year history of life, it is ample time for speciation. Since diverging from a common, less specialized ancestor, chimpanzees and humans have evolved separately for hundreds of thousands of generations. Thus, chimps are not our parent species, but more like our phylogenetic cousins.

Another misconception envisions human evolution as a ladder with a series of steps leading directly from an ancestral anthropoid to *Homo sapiens*. This is often illustrated as a parade of fossil **hominins** (members of the human family) becoming progressively more modern as they march across the page. If human evolution is a parade, then it is a disorderly one, with many splinter groups having traveled down dead ends. At times in hominin history, several human species coexisted **(Figure 17.39)**. Human phylogeny is more like a multibranched bush than a ladder, with our species being the tip of the only twig that still lives.

One more myth is that various human characteristics, such as upright posture and an enlarged brain, evolved in unison. A popular image is of early humans as half-stooped, half-witted cave-dwellers. In fact, the fossil record reveals that different human features evolved at different rates, with erect posture, or bipedalism, leading the way. Our pedigree includes ancestors who walked upright but had ape-sized brains.

Although we can dismiss these misconceptions about human evolution, many fascinating questions about our ancestry still remain. With each new hominin fossil, scientists get a little closer to solving the puzzle of how we became human. In the following pages, you'll learn about some of the important clues that have been discovered so far.



◄ Figure 17.39 A time line of human evolution. The orange bars indicate the time span during which each species lived. Notice that there have been times when two or more hominin species coexisted. The skulls are all drawn to the same scale so you can compare the sizes of craniums and hence brains.

Australopithecus and the Antiquity of Bipedalism

Present-day humans and chimpanzees clearly differ in two major physical features: Humans are bipedal (walk upright) and have much larger brains. When did these features emerge? In the early 1900s, scientists hypothesized that increased brain size was the initial change that separated hominins from other apes. That hypothesis was overturned when a team of researchers in Ethiopia unearthed a stunning 3.24-million-year-old female hominin that had a small brain and walked on two legs **(Figure 17.40a)**. Officially named *Australopithecus afarensis*, but nicknamed Lucy by her discoverers, the individual was only about 3 feet tall and with a head about the size of a softball. Corroborating evidence of early bipedalism was found soon after—the footprints of two upright-walking hominins preserved in a 3.6-million-year-old layer of volcanic ash **(Figure 17.40b)**. Lucy represents just one of several species of *Australopithecus* discovered to date. The first analysis of the most recent addition to the genus, *Australopithecus sediba*, was published in 2010.

Scientists are now certain that bipedalism is a very old trait. Another lineage known as "robust" australopiths—including *Paranthropus boisei* and *Paranthropus robustus* in Figure 17.39—were also small-brained bipeds. So was *Ardipithecus ramidus*, the oldest hominin shown in Figure 17.39.

☑ CHECKPOINT

Which hominin species was the first to walk upright? Which was the first to spread beyond Africa?

Answer: *Australopithecus afarensis*; *Homo erectus*

Homo habilis and the Evolution of Inventive Minds

Enlargement of the human brain is first evident in fossils from East Africa dating to about 2.4 million years ago. Thus, the fundamental human trait of an enlarged brain evolved a few million years after bipedalism. As evolutionary biologist Stephen Jay Gould put it, "Mankind stood up first and got smart later."

Anthropologists have found skulls with brain capacities intermediate in size between those of the latest *Australopithecus* species and those of *Homo sapiens*. Simple handmade stone tools are sometimes found with the larger-brained fossils, which have been dubbed *Homo habilis* ("handy man"). After walking upright for about 2 million years, humans were finally beginning to use their manual dexterity and big brains to invent tools that enhanced their hunting, gathering, and scavenging on the African savanna.

Homo erectus and the Global Dispersal of Humanity

The first species to extend humanity's range from Africa to other continents was *Homo erectus*. Skeletons of *Homo erectus* dating to 1.8 million years ago found in the former Soviet republic of Georgia represent the oldest known fossils of hominins outside Africa. *Homo erectus* was taller than *Homo habilis* and had a larger brain capacity. Intelligence enabled this species to continue succeeding in Africa and also to survive in the colder climates of the north. *Homo erectus* resided in huts or caves, built fires, made clothes from animal skins, and designed stone tools. In anatomical and physiological adaptations, *Homo erectus* was poorly equipped for life outside the tropics, but made up for the deficiencies with cleverness and social cooperation.

Eventually, *Homo erectus* migrated to populate many regions of Asia and Europe, moving as far as Indonesia. Could the "hobbits" (*Homo floresiensis*) from the Biology and Society section have evolved from a long-isolated group of *Homo erectus*? We'll explore that question next. ☑

▼ Figure 17.40 The antiquity of upright posture.



(a) Afar region of Ethiopia, where Lucy was discovered



(b) Ancient footprints



Human Evolution THE PROCESS OF SCIENCE

Who Were the Hobbit People?

How do scientists test hypotheses about events that occurred in the distant past? One approach involves using fossils, the historical record of life on Earth. Researchers have discovered thousands of fossils from at least 20 species of extinct hominins. If you have watched TV shows like *Bones*, in which forensic scientists use skeletal remains to solve crimes, you know that even a small piece of a skeleton can provide a wealth of information to an expert. Researchers have applied this method of hypothesis testing to the scientific debate over the "hobbit" people.

The first **observations** made by the researchers who discovered hominin fossils on the island of Flores revealed that the new fossils did not belong to any known species. This led researchers to ask the **question**, "Where does this hominin fit in our evolutionary history?" The scientists formed the **hypothesis** that the hobbits evolved from an isolated population of *Homo erectus*, the ancient hominin whose far-flung migrations predated those of *Homo sapiens*. They made the **prediction** that key traits of the new species, such as its skull characteristics and body proportions, would resemble those of a miniature *Homo erectus* individual. Rather than a controlled **experiment**, the investigation consisted of making detailed measurements and other observations of the new fossils and comparing them with data from *Homo erectus* fossils. The initial **results** supported their hypothesis.

As you have learned, however, preliminary conclusions are often overturned by new evidence. In the past several years, further analyses have been carried out, and additional specimens have been examined. Many scientists now think that the evidence supports an alternative hypothesis: *Homo floresiensis* is most closely related to *Homo habilis*, a smaller and more ancient species than *Homo erectus*. Other researchers continue to test the hypothesis that the hobbits are not a species at all, but a *Homo sapiens* population with a disorder that caused bone malformations.

How can scientists determine which hypothesis is correct? By accumulating further evidence. While some researchers continue to excavate the site where *Homo floresiensis* was discovered **(Figure 17.41)**, others are widening the search to additional locations. The most helpful information would come from finding a second skull or unearthing bones or teeth from which DNA could be extracted and analyzed. Meanwhile, the mystery of the hobbit people continues.



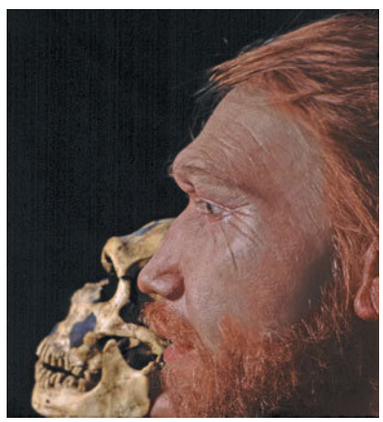
▼ Figure 17.41 Searching for hobbits. Researchers continue to excavate Liang Bua Cave, on the Indonesian island of Flores, where *Homo floresiensis* was discovered.

Homo neanderthalensis

Whether or not it was the immediate ancestor of *Homo floresiensis*, *Homo erectus* did give rise to regionally diverse descendants in Europe and Asia. Among these descendants was *Homo neanderthalensis*—commonly called Neanderthals. This species had a large brain and hunted big game with tools made from stone and wood. Neanderthals were living in Europe as far back as 350,000 years ago and later spread to the Near East; but by 28,000 years ago, the species was extinct.

Do you have a little Neanderthal in you?

Since the first discovery of fossilized remains in the Neander Valley in Germany 150 years ago, people have wondered whether Neanderthals are related to us. Through DNA analysis, researchers have shown that the last common ancestor of humans and Neanderthals lived around 500,000 years ago. However the full Neanderthal genome sequence, completed in 2010, suggests that Neanderthals may have interbred with some populations of *Homo sapiens*. Scientists also learned that the individuals whose DNA was sequenced had pale skin and red hair **(Figure 17.42)**. Further analysis of Neanderthal DNA will undoubtedly reveal more details about the physical appearance and physiology of these intriguing hominins.



▲ Figure 17.42 An artist's rendering of a Neanderthal.

The Origin and Dispersal of *Homo sapiens*

The oldest known fossils of our own species, *Homo sapiens*, were discovered in Ethiopia and date from 160,000 to 195,000 years ago. These early humans lacked the heavy browridges of *Homo erectus* and *Homo neanderthalensis* and were more slender, suggesting that they belong to a distinct lineage. The Ethiopian fossils support molecular evidence about the origin of humans: DNA studies strongly suggest that all living humans can trace their ancestry back to a single African *Homo sapiens* lineage that began 160,000 to 200,000 years ago.

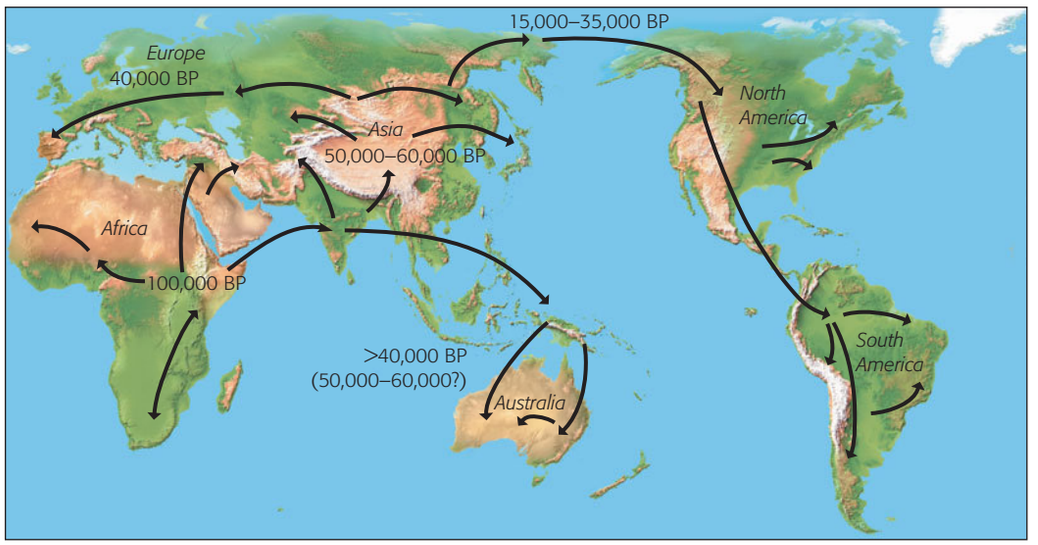
Fossil evidence suggests that our species emerged from Africa in one or more waves, spreading first into Asia and then to Europe and Australia **(Figure 17.43)**. The oldest fossils of *Homo sapiens* outside Africa date back about 50,000 years. The date of the first arrival of humans in the New World is uncertain, although the generally accepted evidence suggests a minimum of 15,000 years ago.

Certain uniquely human traits have allowed for the development of human societies. The primate brain continues to grow after birth, and the period of growth is longer for a human than for any other primate. The extended period of human development also lengthens the time parents care for their offspring, which contributes to the child's ability to benefit from the experiences of earlier generations. This is the basis of **culture**—social transmission of accumulated knowledge, customs, beliefs, and art over generations **(Figure 17.44)**. The major means of this transmission is language, spoken and written. Humans have evolved culturally as well as biologically.

Nothing has had a greater impact on life on Earth than *Homo sapiens*. The global consequences of human evolution have been enormous. Cultural evolution made modern *Homo sapiens* a new force in the history of life—a species that could defy its physical limitations. We do not have to wait to adapt to an environment through natural selection; we simply change the environment to meet our needs.

We are the most numerous and widespread of all large animals, and wherever we go, we bring environmental change faster than many species can adapt; the rate of extinctions during the 1900s was 50 times greater than the average for the past 100,000 years. In the next unit, on ecology, we'll examine the interactions of humans—as well as other species—with the environment. ✓

▼ **Figure 17.43 The spread of *Homo sapiens* (dates given as years before present, BP).**



✓ CHECKPOINT

1. Humans first evolved on which continent?
2. When would a *Homo sapiens* individual have had an opportunity to meet a Neanderthal?

*Answers: **1.** Africa **2.** between the time Homo sapiens reached the regions inhabited by Neanderthals (40,000 to 50,000 years ago) and the time when the Neanderthals died out (28,000 years ago)*



◄ **Figure 17.44 Art history goes back a long way.** Beautiful ancient art, such as this 30,000-year-old cave painting, is just one example of our cultural roots in early societies.



Human Evolution EVOLUTION CONNECTION

Are We Still Evolving?

Imagine that you could take a time machine 100,000 years into the past and bring back a *Homo sapiens* man. If you dressed him in jeans and a T-shirt and took him for a stroll around campus, chances are that no one would look twice. Did we stop evolving after becoming *Homo sapiens*? In some ways, yes. The human body has not changed much in the past 100,000 years. And by the time *Homo sapiens* began to travel out of Africa, all of the complex characteristics that define our humanity, including our big-brained intelligence and our capacity for language and symbolic thought, had already evolved.

But as humans wandered far from their site of origin and settled in diverse environments, populations encountered different selective forces. Some traits of people today reflect evolutionary responses of ancient ancestors to their environment, including disease, diet, and physical factors. For example, certain populations evolved sickle hemoglobin as an adaptation to the deadly disease malaria (see the Evolution Connection section of Chapter 13). Populations that kept dairy herds evolved the ability to digest lactose as adults (see the Evolution Connection section of Chapter 3). One of the most striking differences among people is skin color **(Figure 17.45)**. The loss of skin pigmentation in humans who migrated north from Africa is thought to be an adaptation to low levels of ultraviolet (UV) radiation in northern latitudes. Dark pigment blocks the UV radiation necessary for synthesizing vitamin D—essential for proper bone development—in the skin. Recent research has turned up numerous other examples of adaptations that enabled us to colonize Earth's varied environments. For instance, Tibetans live at altitudes up to 14,000 feet (2.6 miles), where the air has 40% less oxygen than at sea level. Researchers have identified genes that have undergone evolutionary changes in response to this challenging environment **(Figure 17.46)**. Despite evolutionary tweaks such as these, however, we remain a single species.

Figure 17.45 **People with different adaptations to UV radiation.**



Figure 17.46 **Tibetans, a population adapted to living at high altitude.**



Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

The Origins of Animal Diversity

What Is an Animal?

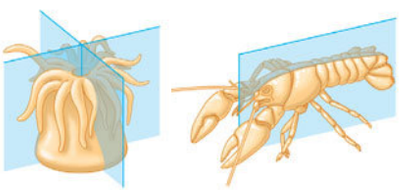
Animals are eukaryotic, multicellular, heterotrophic organisms that obtain nutrients by ingestion. Most animals reproduce sexually and develop from a zygote to a blastula and then to a gastrula. After the gastrula stage, some develop directly into adults, whereas others pass through a larval stage.

Early Animals and the Cambrian Explosion

Animals probably evolved from a colonial, flagellated protist. Precambrian animals were soft-bodied. Animals with hard parts appeared during the Cambrian period. Between 535 and 525 million years ago, animal diversity increased rapidly.

Animal Phylogeny

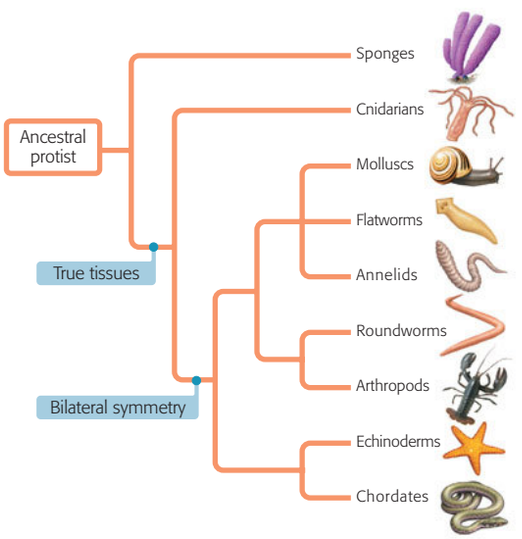
Major branches of animal evolution are defined by two key evolutionary differences: the presence or absence of tissues and radial versus bilateral body symmetry. A body cavity (coelom) at least partly lined by mesoderm evolved in a number of later branches.



Radial symmetry Bilateral symmetry

Major Invertebrate Phyla

This tree shows the eight major invertebrate phyla, as well as chordates, which include a few invertebrates.



Sponges

Sponges (multiple phyla) are stationary animals with porous bodies but no true tissues. Specialized cells draw water through pores in the sides of the body and trap food particles.

Cnidarians

Cnidarians (phylum Cnidaria) have radial symmetry, a gastrovascular cavity with a single opening, and tentacles with stinging cnidocytes. The body is either a stationary polyp or a floating medusa.

Molluscs

Molluscs (phylum Mollusca) are soft-bodied animals often protected by a hard shell. The body has three main parts: a muscular foot, a visceral mass, and a fold of tissue called the mantle.

MOLLUSCS		
Gastropods	**Bivalves**	**Cephalopods**
		

Flatworms

Flatworms (phylum Platyhelminthes) are the simplest bilateral animals. They may be free-living (such as planarians) or parasitic (such as tapeworms).

Annelids

Annelids (phylum Annelida) are segmented worms with complete digestive tracts. They may be free-living or parasitic.

Roundworms

Roundworms, also called nematodes (phylum Nematoda), are unsegmented and cylindrical with tapered ends. They may be free-living or parasitic.

Arthropods

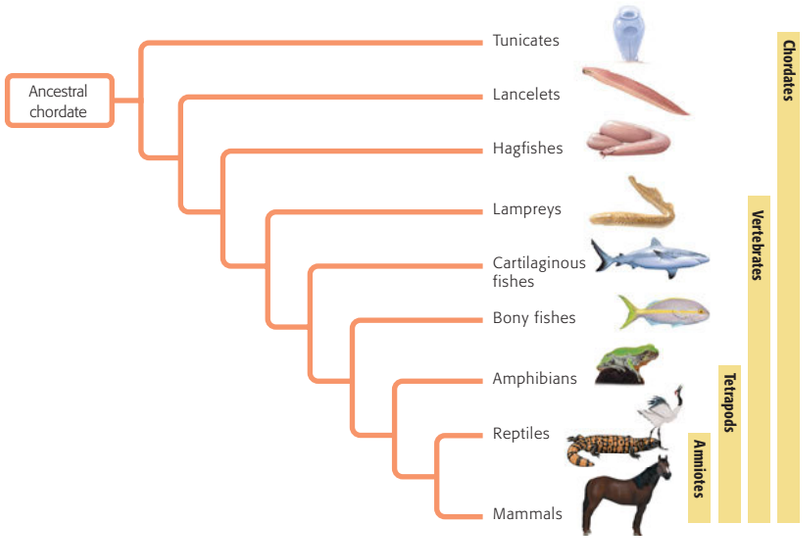
Arthropods (phylum Arthropoda) are segmented animals with an exoskeleton and specialized, jointed appendages.

ARTHROPODS			
Arachnids	**Crustaceans**	**Millipedes and Centipedes**	**Insects**
			

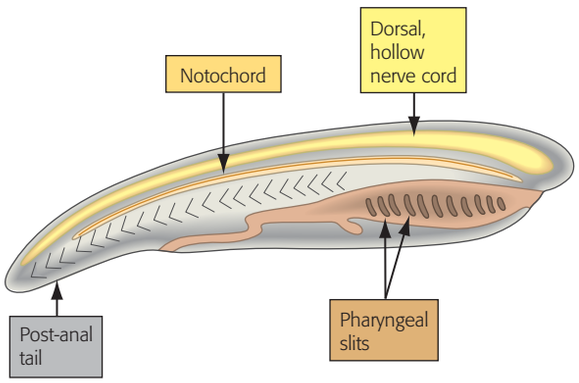
Echinoderms

Echinoderms (phylum Echinodermata) are stationary or slow-moving marine animals that lack body segments and possess a unique water vascular system. Bilaterally symmetric larvae usually change to radially symmetric adults. Echinoderms have a bumpy endoskeleton.

Vertebrate Evolution and Diversity



Characteristics of Chordates



Tunicates and lancelets are invertebrate chordates. The vast majority of chordates are vertebrates, possessing a cranium and backbone.

Fishes

Hagfishes have skulls but lack vertebrae. Lampreys are jawless vertebrates. Cartilaginous fishes, such as sharks, are mostly predators with powerful jaws and a flexible skeleton made of cartilage. Bony fishes have a stiff skeleton reinforced by calcium. Bony fishes are further classified into ray-finned fishes and lobe-finned fishes (including lungfishes).

Amphibians

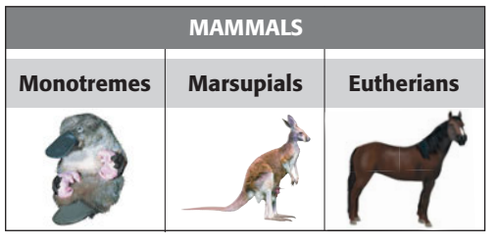
Amphibians are tetrapod vertebrates that usually deposit their eggs (lacking shells) in water. Aquatic larvae typically undergo a radical metamorphosis into the adult stage. Their moist skin requires that amphibians spend much of their adult life in humid environments.

Reptiles

Reptiles are amniotes, vertebrates that develop in a fluid-filled egg enclosed by a shell. Reptiles include terrestrial ectotherms with lungs and waterproof skin covered by scales. Scales and amniotic eggs enhanced reproduction on land. Birds are endothermic reptiles with wings, feathers, and other adaptations for flight.

Mammals

Mammals are endothermic vertebrates with mammary glands and hair. There are three major groups: Monotremes lay eggs; marsupials use a placenta but give birth to tiny embryonic offspring that usually complete development while attached to nipples inside the mother's pouch; and eutherians, or placental mammals, use their placenta in a longer-lasting association between the mother and her developing young.



The Human Ancestry

The Evolution of Primates

The first primates were small, arboreal mammals that evolved from insect-eating mammals about 65 million years ago. Anthropoids consist of New World monkeys (with prehensile tails), Old World monkeys (without prehensile tails), apes, and humans.

The Emergence of Humankind

Chimpanzees and humans evolved from a common ancestor about 5–7 million years ago. Species of the genus *Australopithecus*, which lived at least 4 million years ago, walked upright and had a small brain. Enlargement of the human brain in *Homo habilis* came later, about 2.4 million years ago. *Homo erectus* was the first species to extend humanity's range from its birthplace in Africa to other continents. *Homo erectus* gave rise to regionally diverse descendants, such as the Neanderthals (*Homo neanderthalensis*). Current data indicate a relatively recent dispersal of modern Africans that gave rise to today's human diversity.

SELF-QUIZ

1. Bilateral symmetry in the animal kingdom is best correlated with
   a. an ability to sense equally in all directions.
   b. the presence of a skeleton.
   c. motility and active predation and escape.
   d. development of a true coelom.
2. The cavity between your outer body wall and your digestive tract that is fully lined by mesoderm is an example of a true _____. Roundworms have a _____, a body cavity not completely lined by mesoderm.

3. Identify which of the following categories includes all others in the list: arthropod, arachnid, insect, butterfly, crustacean, millipede.
4. The oldest group of tetrapods is the _____.
5. Reptiles are much more extensively adapted to life on land than amphibians because reptiles
   a. have a complete digestive tract.
   b. lay eggs that are enclosed in shells.
   c. are endothermic.
   d. go through a larval stage.
6. What is the name of the phylum to which humans belong? For what anatomical structure is the phylum named? Where in your body is a derivative of this anatomical structure found?
7. Fossils suggest that the first major trait distinguishing human primates from other primates was _____.
8. Which of the following types of animals is not included in the human ancestry? (*Hint*: See Figure 17.30.)
   a. a bird
   b. a bony fish
   c. an amphibian
   d. a primate
9. Put the following list of species in order, from the oldest to the most recent: *Homo erectus*, *Australopithecus* species, *Homo habilis*, *Homo sapiens*.
10. Match each of the following animals to its phylum:

a. human	1. Echinodermata
b. leech	2. Arthropoda
c. sea star	3. Cnidaria
d. lobster	4. Chordata
e. sea anemone	5. Annelida

Answers to these questions can be found in Appendix: Self-Quiz Answers.

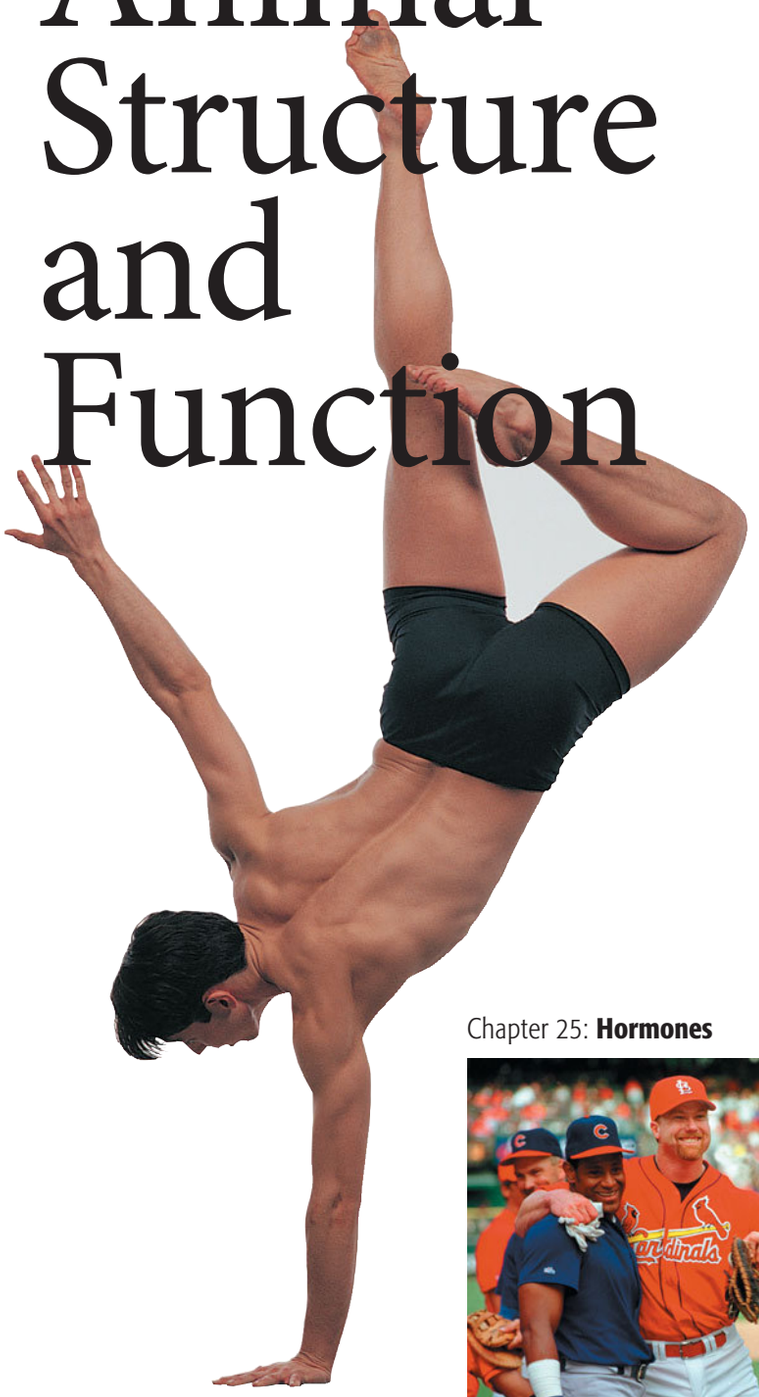
THE PROCESS OF SCIENCE

11. Imagine that you are a marine biologist. As part of your exploration, you dredge up an unknown animal from the seafloor. Describe some of the characteristics you should look at to determine the phylum to which the creature should be assigned.
12. Many people describe themselves as vegetarians. Strictly speaking, vegetarians eat only plant products. Most vegetarians are not, in fact, that strict. Interview acquaintances who describe themselves as vegetarians and determine which taxonomic groups they avoid eating (see Figures 17.6 and 17.30). Try to generalize about their diet. For example, do they avoid eating vertebrates but eat some invertebrates? Do they avoid only birds and mammals? Do they eat dairy products or eggs?
13. Some researchers think that drying and cooling of the climate caused expansion of the African savanna and that this environment favored upright walking in early humans. Why might bipedalism be advantageous in the savanna? How might an erect posture relate to the evolution of a larger brain?

BIOLOGY AND SOCIETY

14. Coral reefs harbor a greater diversity of animals than any other environment in the sea. Australia's Great Barrier Reef has been protected as a marine reserve and is a mecca for scientists and nature enthusiasts. Elsewhere, such as in Indonesia and the Philippines, coral reefs are in danger. Many reefs have been depleted of fish, and runoff from the shore has covered coral with sediment. Nearly all the changes in the reefs can be traced back to human activities. What kinds of activities do you think might be contributing to the decline of the reefs? What are some reasons to be concerned about this decline? Do you think the situation is likely to improve or worsen in the future? Why? What might the local people do to halt the decline? Should the more industrialized countries help? Why or why not?
15. The human body has not changed much in the last 100,000 years, but human culture has changed a great deal. As a result of our culture, we change the environment at a rate far greater than the rate at which many species, including our own, can evolve. What evidence of rapid environmental change do you see regularly? What aspects of human culture are responsible for these changes? Do you see any evidence of a decrease in the rate of human-caused environmental changes?

Unit 5 Animal Structure and Function



Chapter 21: **Unifying Concepts of Animal Structure and Function**



Chapter Thread: **Controlling Body Temperature**

Chapter 22: **Nutrition and Digestion**



Chapter Thread: **Controlling Your Weight**

Chapter 23: **Circulation and Respiration**



Chapter Thread: **Athletic Endurance**

Chapter 24: **The Body's Defenses**

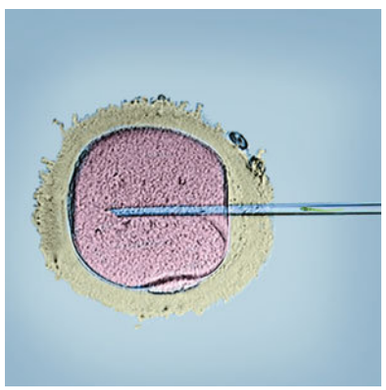


Chapter Thread: **HIV and AIDS**

Chapter 25: **Hormones**

Chapter Thread: **Steroid Abuse**

Chapter 26: **Reproduction and Development**



Chapter Thread: **High-Tech Babies**

Chapter 27: **Nervous, Sensory, and Locomotor Systems**



Chapter Thread: **Extrahuman Senses**

21 Unifying Concepts of Animal Structure and Function



Keeping cool.
Sweating and drinking water are two ways of cooling the human body.

CHAPTER CONTENTS

The Structural Organization of Animals 456
Exchanges with the External Environment 464
Regulating the Internal Environment 465

CHAPTER THREAD
Controlling Body Temperature

BIOLOGY AND SOCIETY
An Avoidable Tragedy 455
THE PROCESS OF SCIENCE
How Does a Python Warm Her Eggs? 468
EVOLUTION CONNECTION
Adaptations for Thermoregulation 471



Controlling Body Temperature BIOLOGY AND SOCIETY

An Avoidable Tragedy

August 20, 2008, started off as a normal day for the football team at Pleasure Ridge Park High School. True, the day was sweltering, with a heat index of 94, but such conditions are common during Kentucky summers. However, this day turned tragic when Max Gilpin, a healthy 15-year-old sophomore offensive lineman, began to have trouble breathing during the team's routine training and collapsed. By the time he reached the hospital, his body temperature was 107 degrees Fahrenheit. Max died three days later from heat stroke. As heartbreaking as it is, this case is hardly unique: Heat illness is a leading cause of death and injury among U.S. high school athletes, affecting nearly 10,000 each year.

When you play or work hard, your muscles produce a lot of heat. In response, a temperature control center in your brain initiates responses that help keep your internal temperature near its normal value (about 37°C, or 99°F). Sweating cools your skin by evaporation and blood vessels near the skin surface expand, allowing more heat to be released. But what if the heat worsens? Surface blood vessels widen to their maximum, and excessive sweating may cause dehydration. Both of these responses could lower blood pressure enough to cause you to faint. This set of symptoms, called heat exhaustion, represents the body's final attempt to cool itself. To avoid heat exhaustion, you should drink plenty of water and rest if you feel lightheaded or your skin flushes excessively.

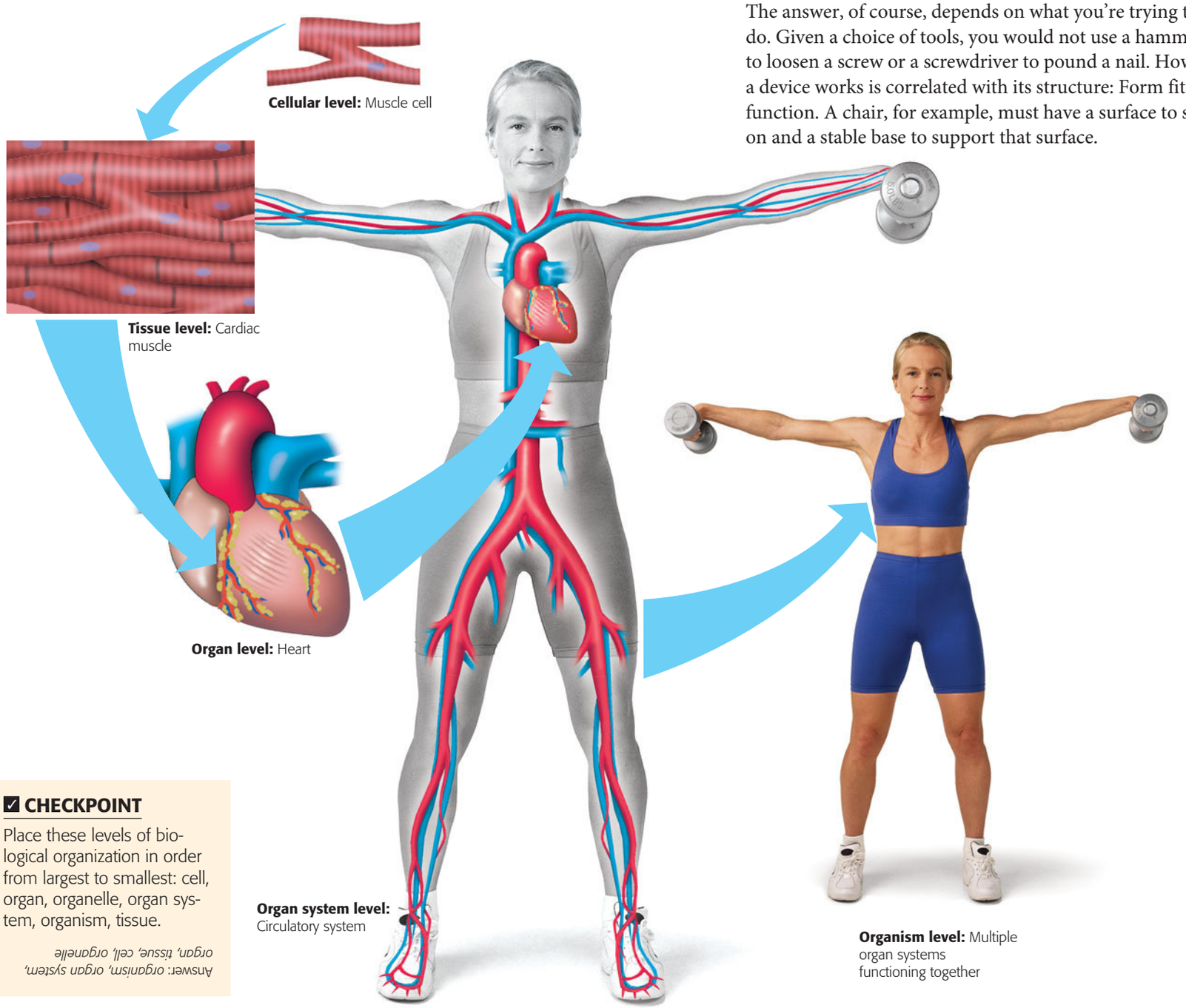
Under extreme conditions, a severely elevated body temperature can disrupt the brain's control center. When the body loses its ability to self-regulate, sweating stops and the skin becomes hot and dry. The body's organs begin to fail as a result of the extreme heat, and brain damage and death can quickly follow unless the body is rapidly cooled and provided with fluids. This condition, called heat stroke, is caused by a total breakdown of the body's internal temperature control system.

In this unit, you will learn how your body works, including its self-regulating mechanisms. We'll concentrate on humans but offer comparisons to other animals to provide examples of different solutions to a common set of problems. How, for example, do creatures as diverse as hydras, halibut, and humans regulate body temperature or obtain food? By learning about various evolutionary adaptations common to animals, you will better understand your own body. To set the stage for the rest of the unit, this chapter begins with a description of basic animal structure, from cells to tissues to organs to organ systems. Next, these structural principles will be applied to two examples of how animals regulate their internal environment: the control of temperature and the control of water and solute movement.

The Structural Organization of Animals

Life is characterized by a hierarchy of organization. In animals, individual cells are grouped into tissues, which in turn are grouped into organs, which participate in organ systems, which together make up the entire organism **(Figure 21.1)**. Parts of the body at each level of the hierarchy act together to perform the functions of life, such as regulating an animal's internal environment. For example, regulation of your body temperature requires the cooperation of several levels of body organization. The brain, an organ, sends signals via the nervous system that trigger specific changes in tissues (such as the narrowing or widening of capillaries near the skin) and individual cells (such as an increase or decrease in glucose metabolism). The result is a change within the whole body. ☑

▼Figure 21.1 Structural hierarchy in a human.



Form Fits Function

Which is the better tool: a hammer or a screwdriver? The answer, of course, depends on what you're trying to do. Given a choice of tools, you would not use a hammer to loosen a screw or a screwdriver to pound a nail. How a device works is correlated with its structure: Form fits function. A chair, for example, must have a surface to sit on and a stable base to support that surface.

☑ CHECKPOINT

Place these levels of biological organization in order from largest to smallest: cell, organ, organelle, organ system, organism, tissue.

Answer: organism, organ system, organ, tissue, cell, organelle

These structural elements are dictated by the task that the chair must perform. The same principle applies to life at its many structural levels, from cells to organisms. Analyzing a biological structure gives us clues about what it does and how it works. Conversely, knowing the function of a structure provides insight about its construction. In exploring life at its many levels, we will discover functional elegance at every turn **(Figure 21.2)**.

When discussing structure and function, biologists distinguish anatomy from physiology. **Anatomy** is the study of the structure of an organism's parts. **Physiology** is the study of the function of those parts. For example, an anatomist might study the arrangement of blood vessels near the surface of the skin, whereas a physiologist might study how those blood vessels widen in response to a sudden rise in temperature. Despite their different approaches, the two disciplines serve the same purpose: to better understand the connections between structure and function.

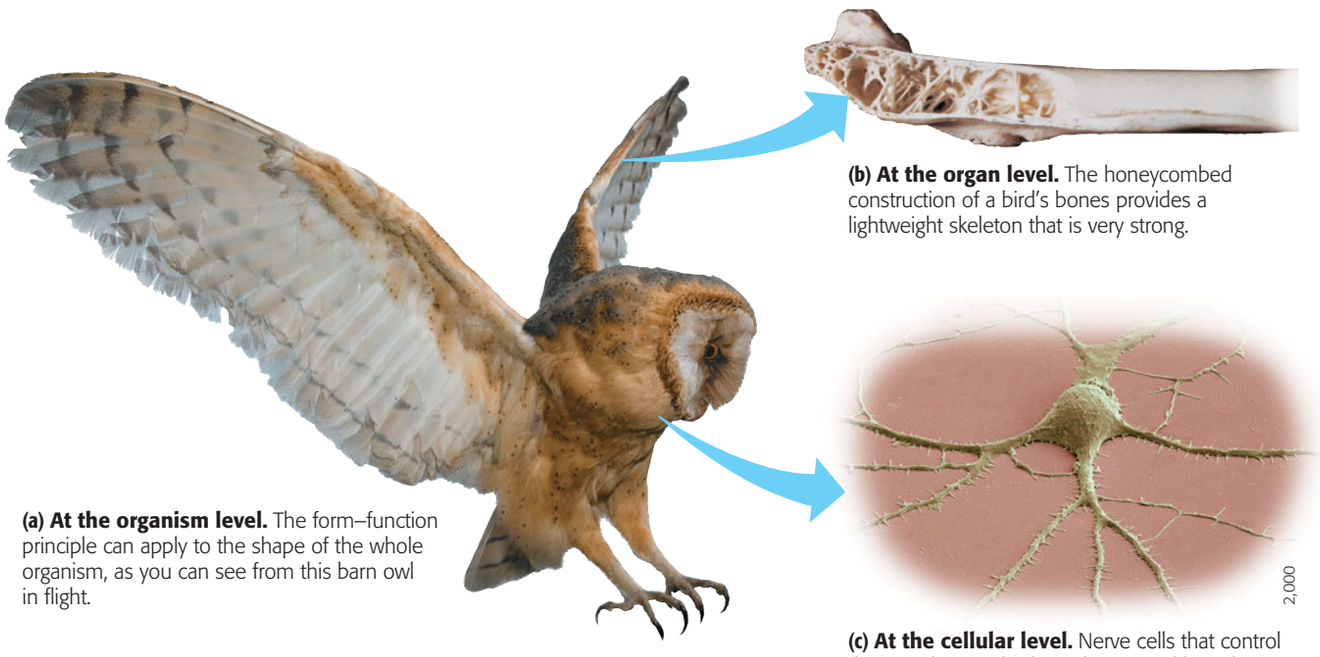
The correlation of form (structure) and function is a fundamental principle of biology that is evident at all levels of life's hierarchy; it is a principle that will guide us throughout our study of animals. But this rule of "design" does not mean that such biological tools as a bird's wings, a fish's gills, or a mammal's blood vessels are products of purposeful invention. Here the analogy to household tools such as hammers and screwdrivers fails because those tools were designed with specific goals. It is natural selection that refines biological equipment to the current environment. It does so by screening for the most effective variations among individuals of a population—those variations that are most advantageous in the local environment. Generations of selecting for what works best in a particular environment will fit form to function without any goal-oriented plan. Thus, the form–function principle is just another facet of biology's unifying theme: evolution. ☑

Tissues

The cell is the basic unit of all living organisms. In almost all animals, including humans, cells rarely act alone but instead are grouped into tissues. A **tissue** is an integrated group of similar cells that performs a specific function. The cells composing a tissue are specialized; they have an overall structure that enables them to perform a specific task.

Some tissues consist of living cells surrounded by a meshwork of nonliving fibers. The cells of other tissues are held together by a sticky substance that coats the cells or by special junctions that fuse the cells together. An animal has four main categories of tissue: epithelial tissue, connective tissue, muscle tissue, and nervous tissue. As you'll see, the structure of each type of tissue relates to its specific function.

▼Figure 21.2 Form fits function.



(a) At the organism level. The form–function principle can apply to the shape of the whole organism, as you can see from this barn owl in flight.

(b) At the organ level. The honeycombed construction of a bird's bones provides a lightweight skeleton that is very strong.

(c) At the cellular level. Nerve cells that control the muscles of a bird or other animal have long extensions that transmit signals.

☑ CHECKPOINT

1. What is the difference between anatomy and physiology?
2. Explain how a tennis racket illustrates the "form fits function" principle.

Answers: **1.** *Anatomy is the study of structure, whereas physiology is the study of function.* **2.** *To aid the function of hitting a ball, a tennis racket has a handle for gripping, a large head to strike the ball, and strings to provide bounce.*

Epithelial Tissue

The tissue that covers the surface of the body and lines organs is called **epithelial tissue**, also known as **epithelium** (Figure 21.3). The epidermis (outer layer of skin) and the linings of the heart, blood vessels, and digestive tract are examples. Epithelial tissue is made of sheets of tightly packed cells that are fused together. The architecture of an epithelium illustrates how structure fits function at the tissue level. For example, your epidermis contains dense layers of tightly bound epithelial cells, forming a protective barrier that surrounds your body and helps protect its internal environment from external threats.

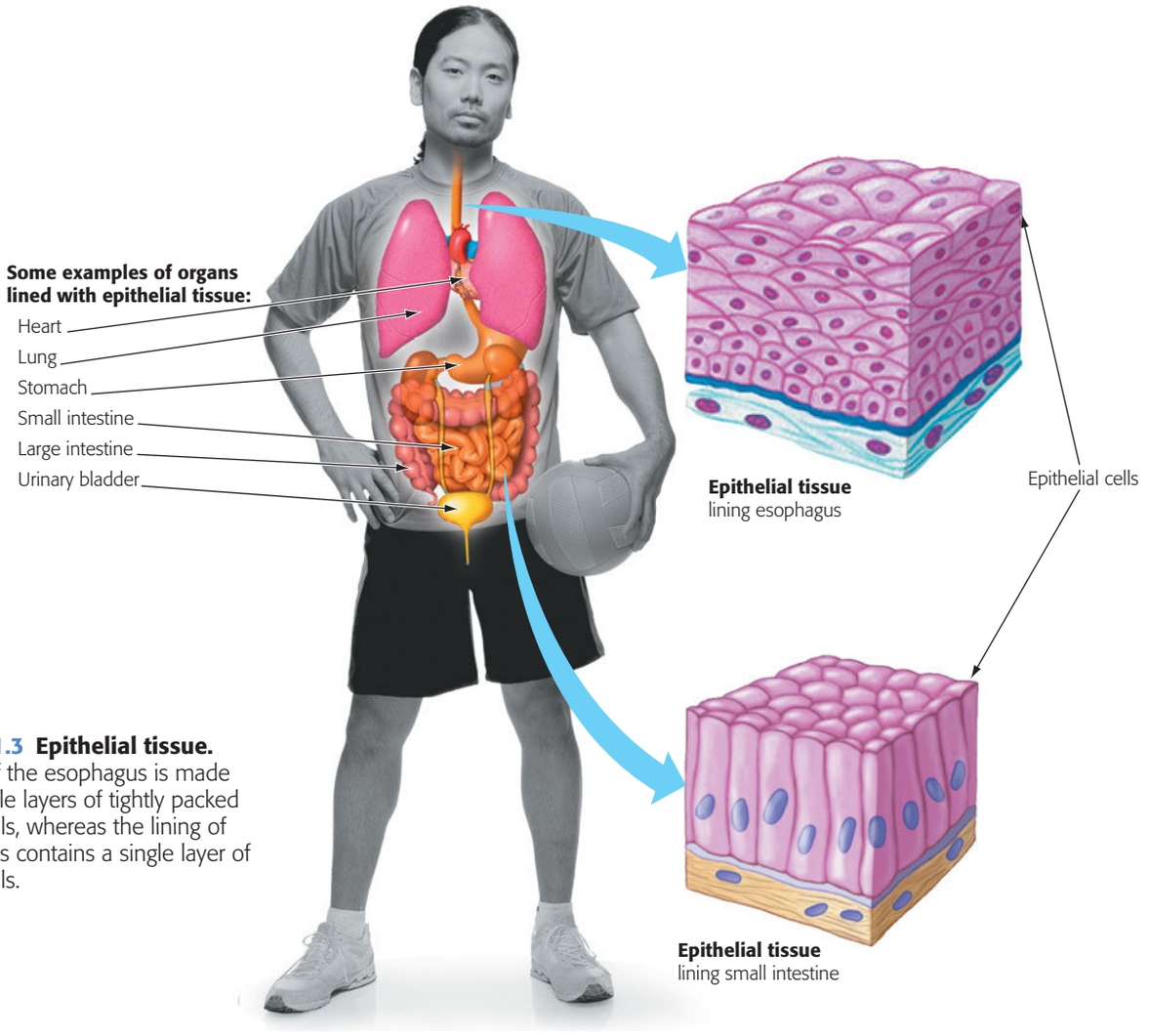
The body continuously renews the cells of epithelial tissue, shedding old cells and growing new ones. For example, cells of the epidermis continuously fall off and are renewed about every two weeks. Such turnover requires rapid cell division, which increases the risk of an error in cell division that leads to cancer. And compared with other body tissues, epithelium that contacts the environment directly is exposed to much higher levels of carcinogens (smoke in the lungs and UV light on the skin, for example). Consequently, about 80% of all cancers (including skin, lung, and breast cancer) arise in epithelial tissue. Cancers of the epithelium are called carcinomas.

Connective Tissue

In contrast to epithelium, with its tightly packed cells, **connective tissue** has a sparse population of cells scattered throughout a jellylike material called the **extracellular matrix**. The matrix consists of a web of protein fibers embedded in a liquid (as in blood), jelly (as in fat tissue), or solid (as in bone).

The structure of connective tissue corresponds to its function: to bind and support other tissues. For example, the epithelial tissue of your skin (epidermis) lies on top of a layer of connective tissue called the dermis, which contains the blood vessels and extracellular fluids that nourish the epidermis.

Figure 21.4 illustrates six of the major types of connective tissue. The most widespread connective tissue in the body of vertebrates (animals with backbones, including humans) is **loose connective tissue** (Figure 21.4a). It binds epithelia to underlying tissues and holds organs in place, similar to the way that packing peanuts can prevent shipped merchandise from sliding around. This connective tissue is held together by a mesh of protein fibers that provide great strength and elasticity. For example, if someone pinches your cheek, it is protein fibers that



► **Figure 21.3 Epithelial tissue.** The lining of the esophagus is made up of multiple layers of tightly packed epithelial cells, whereas the lining of the intestines contains a single layer of epithelial cells.

keep your flesh in place and allow it to quickly snap back. A decrease in production of one of these proteins (collagen) as we age can result in skin wrinkles; some people inject collagen in an attempt to restore smooth skin.

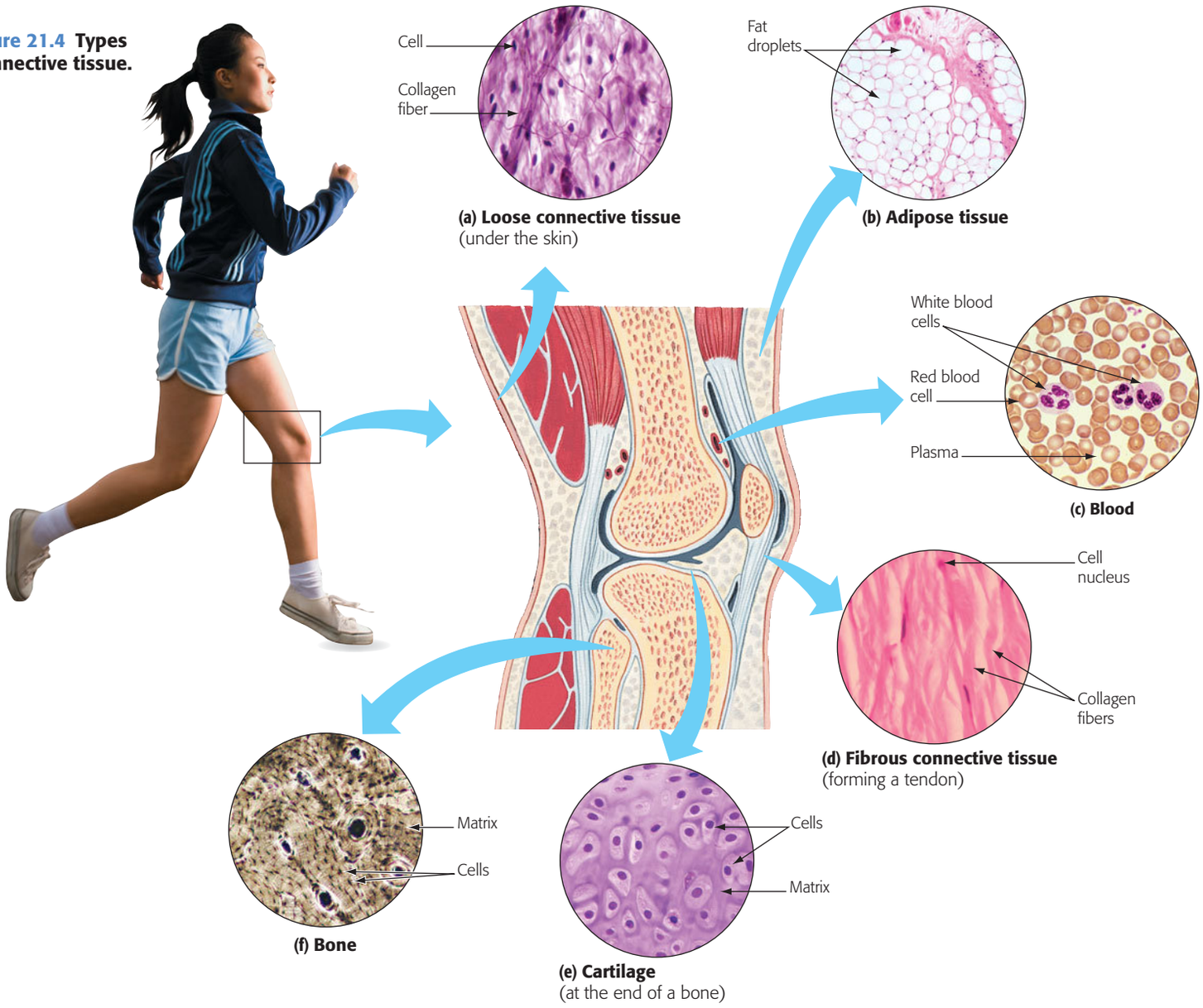
Adipose tissue stores fat in closely packed cells (Figure 21.4b). This tissue stockpiles energy while also padding and insulating the body. Each adipose cell contains a large globule of fat (mostly triglycerides—see Figure 3.11b); the cell swells when fat is stored and shrinks when fat is used for energy. Gaining body fat involves increasing the size of your fat cells, not creating new fat cells.

Blood is a connective tissue consisting of red and white blood cells suspended in a liquid called plasma (Figure 21.4c). Blood functions mainly in transporting substances from one part of the body to another and also plays a major role in immunity.

The other three types of connective tissue have cells suspended in dense matrices. **Fibrous connective tissue** has a dense matrix of collagen. It forms tendons, which attach muscles to bones, and ligaments, which join bones together at joints (Figure 21.4d). The matrix of **cartilage** is strong but flexible (Figure 21.4e). Use your finger to flip your outer ear, and you'll get the idea of how cartilage functions as a flexible, boneless skeleton. The cartilaginous fishes—which include sharks and rays—have skeletons made entirely from cartilage. Cartilage is often found at the end of bones where it forms shock-absorbing pads. Cartilage has no blood vessels, so injuries to it (football knee injuries, for example) tend to heal very slowly, if at all. **Bone** is a rigid connective tissue with a matrix of collagen fibers hardened with deposits of calcium salts. This combination makes bone hard without being brittle (Figure 21.4f).

Why are knee injuries often long-lasting?

► **Figure 21.4 Types of connective tissue.**



Muscle Tissue

Muscle is the most abundant tissue in most animals. In fact, what we call "meat" on the menu is mostly animal muscle. **Muscle tissue** consists of bundles of long, thin, cylindrical cells called muscle fibers. Each cell has specialized proteins arranged into a structure that contracts (pulls in) when the cell is stimulated by a signal from a nerve. Humans and other vertebrates have three types of this contractile tissue, each with a slightly different structure: skeletal muscle, cardiac (heart) muscle, and smooth muscle.

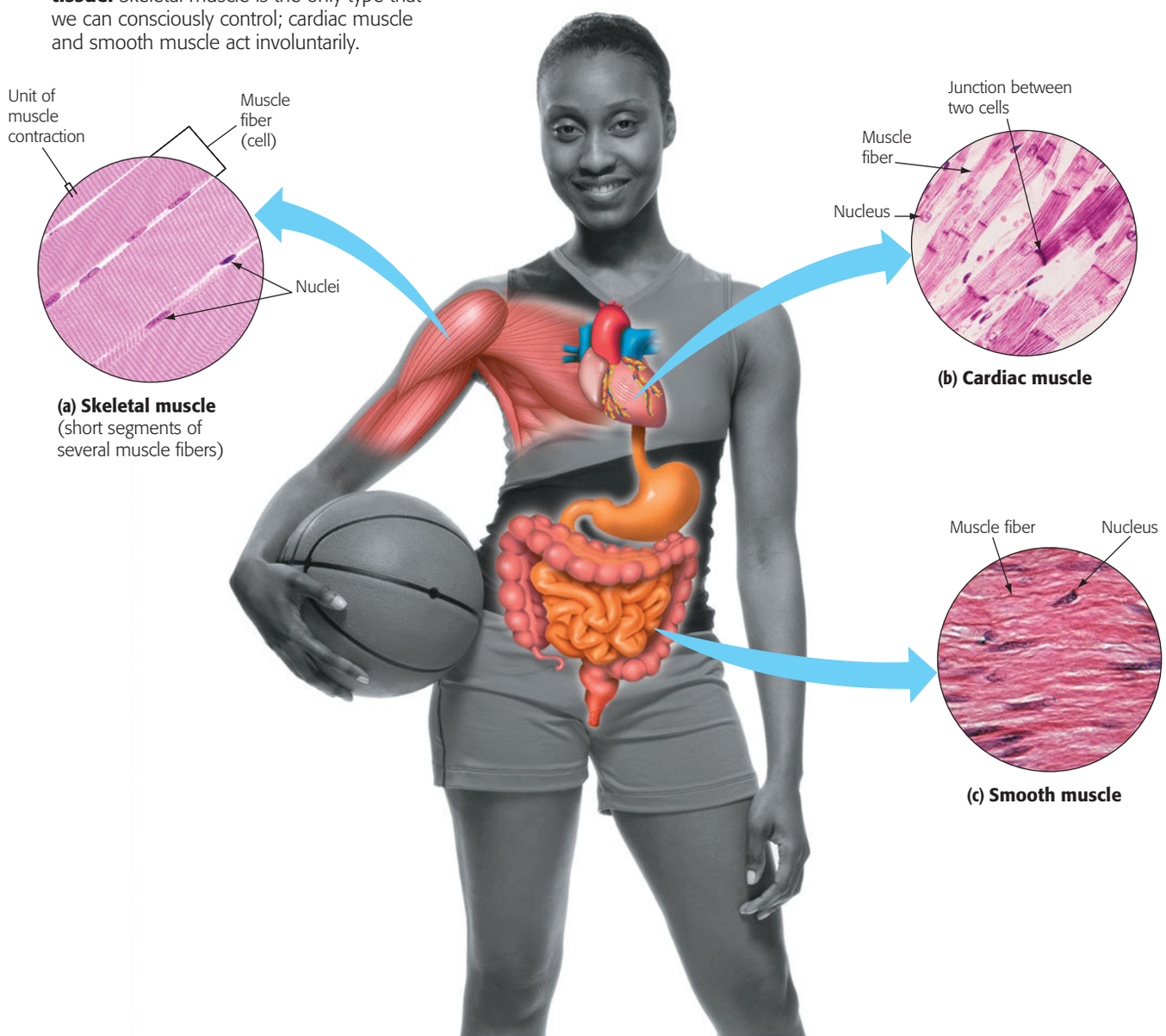
Skeletal muscle is attached to your bones by tendons and is responsible for your voluntary movements, such as walking and talking **(Figure 21.5a)**. This type of muscle is said to be striated (striped) because the contractile proteins form a banded pattern. Adults have a fixed number of these cells. Weight training does not increase the number of muscle cells but instead enlarges those already present.

What effect does working out have on your muscles?

Cardiac muscle is found only in heart tissue **(Figure 21.5b)**. The contraction of the cardiac muscle produces the heartbeat. Cardiac muscle cells are branched and joined to one another, appearing like one large interconnected mass of muscle. This structure allows the contraction signal to be propagated quickly to all muscle cells at once, producing a coordinated beat. Cardiac muscle is an involuntary muscle, meaning that your heart contracts without any conscious control on your part.

In contrast to skeletal muscle and cardiac muscle, **smooth muscle** is named for its lack of obvious stripes **(Figure 21.5c)**. Found in the walls of such organs as the intestines and blood vessels, smooth muscle is involuntary. For example, you have no control over the dilation of your blood vessels in response to heat, a response that causes you to flush. Smooth muscle contracts more slowly than skeletal muscle, but it can remain contracted for a longer time.

▼Figure 21.5 Three types of muscle tissue. Skeletal muscle is the only type that we can consciously control; cardiac muscle and smooth muscle act involuntarily.

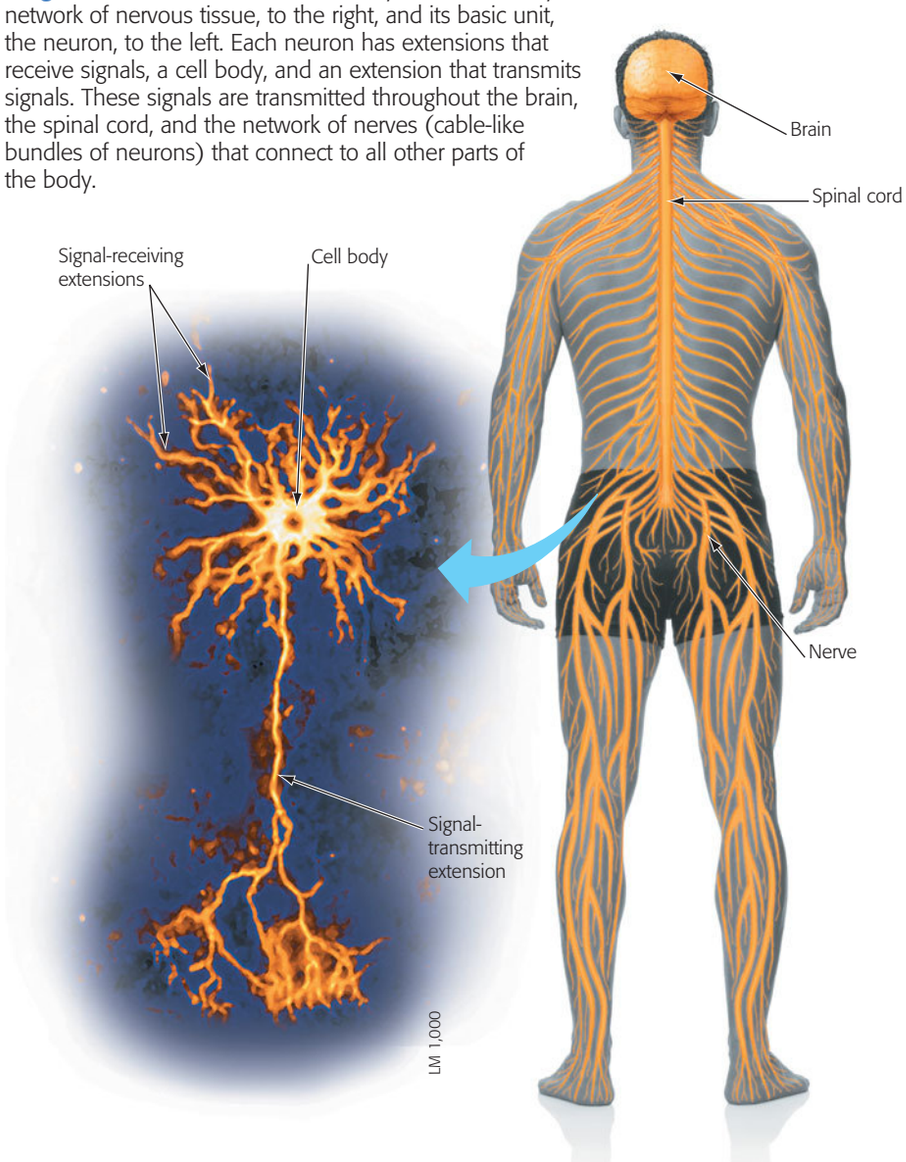


Nervous Tissue

Most animals are active creatures that respond rapidly to stimuli from their environment. For example, if you touch a very hot object, your arm quickly jerks away. This response requires information to be relayed from one part of the body to another. It is **nervous tissue** that makes such communication possible. Nervous tissue is found in your brain and spinal cord, as well as in the nerves that connect them to all other parts of your body.

The basic unit of nervous tissue is the **neuron**, or nerve cell **(Figure 21.6)**. With their long extensions, neurons can transmit electrical signals very rapidly over long distances. For example, neurons in the sciatic nerve of your leg may be as long as 1 m (3.3 feet), running all the way from the base of your spinal cord to the tips of your toes. You are wired for action—and for thinking, since it is the network of neurons in your brain that functions as your mind. ☑

▼Figure 21.6 Nervous tissue. Here you see the body's network of nervous tissue, to the right, and its basic unit, the neuron, to the left. Each neuron has extensions that receive signals, a cell body, and an extension that transmits signals. These signals are transmitted throughout the brain, the spinal cord, and the network of nerves (cable-like bundles of neurons) that connect to all other parts of the body.



Organs and Organ Systems

After tissues, the next level in the structural hierarchy is the organ. An **organ** consists of two or more tissues packaged into one working unit that performs a specific function. Your heart, brain, and small intestine are examples of organs. At each level of the hierarchy, functions emerge from the collective interaction of the structures at lower levels. An organ performs functions that none of its component tissues can carry out alone.

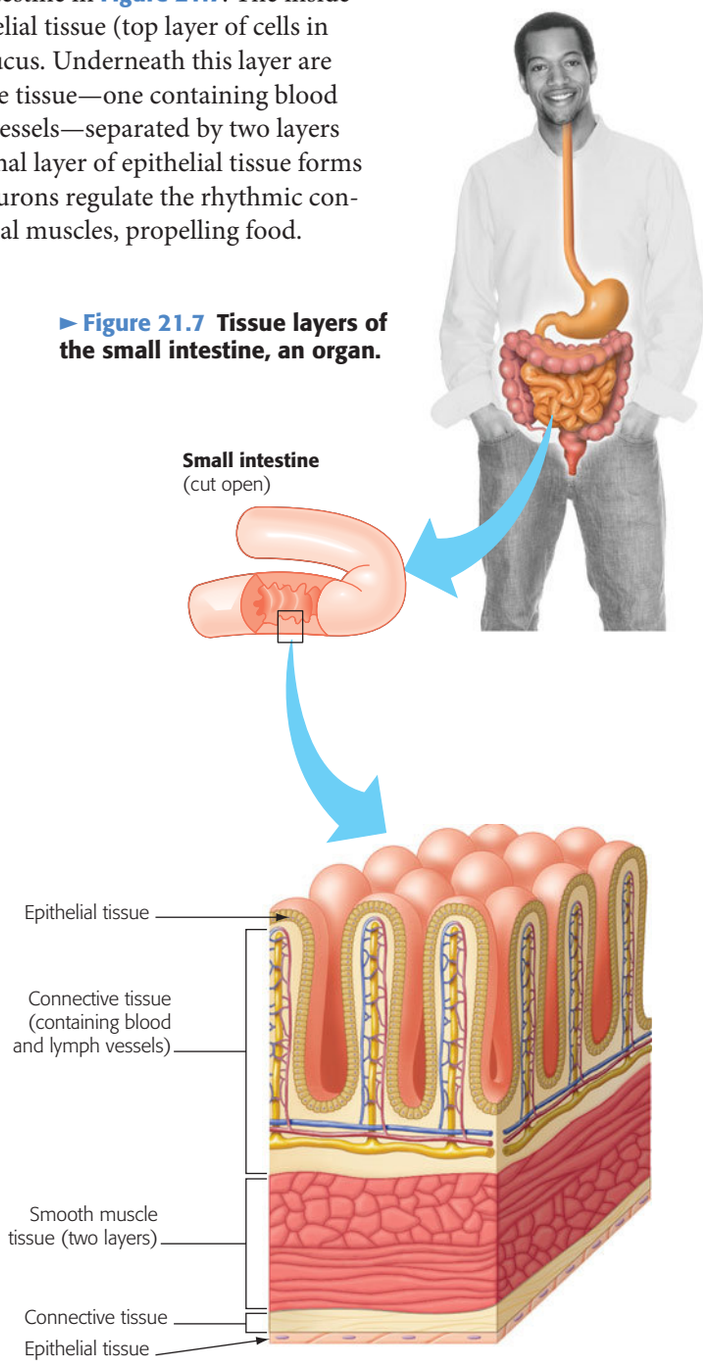
To see how multiple tissues coordinate a single organ, examine the layered arrangement of tissues in the wall of the small intestine in **Figure 21.7**. The inside wall is lined with epithelial tissue (top layer of cells in figure) that secretes mucus. Underneath this layer are two layers of connective tissue—one containing blood capillaries and lymph vessels—separated by two layers of smooth muscle. A final layer of epithelial tissue forms the outside surface. Neurons regulate the rhythmic contractions of the intestinal muscles, propelling food.

☑ CHECKPOINT

Name the four types of tissue found in most organs.

Answer: epithelial, connective, muscle, and nervous

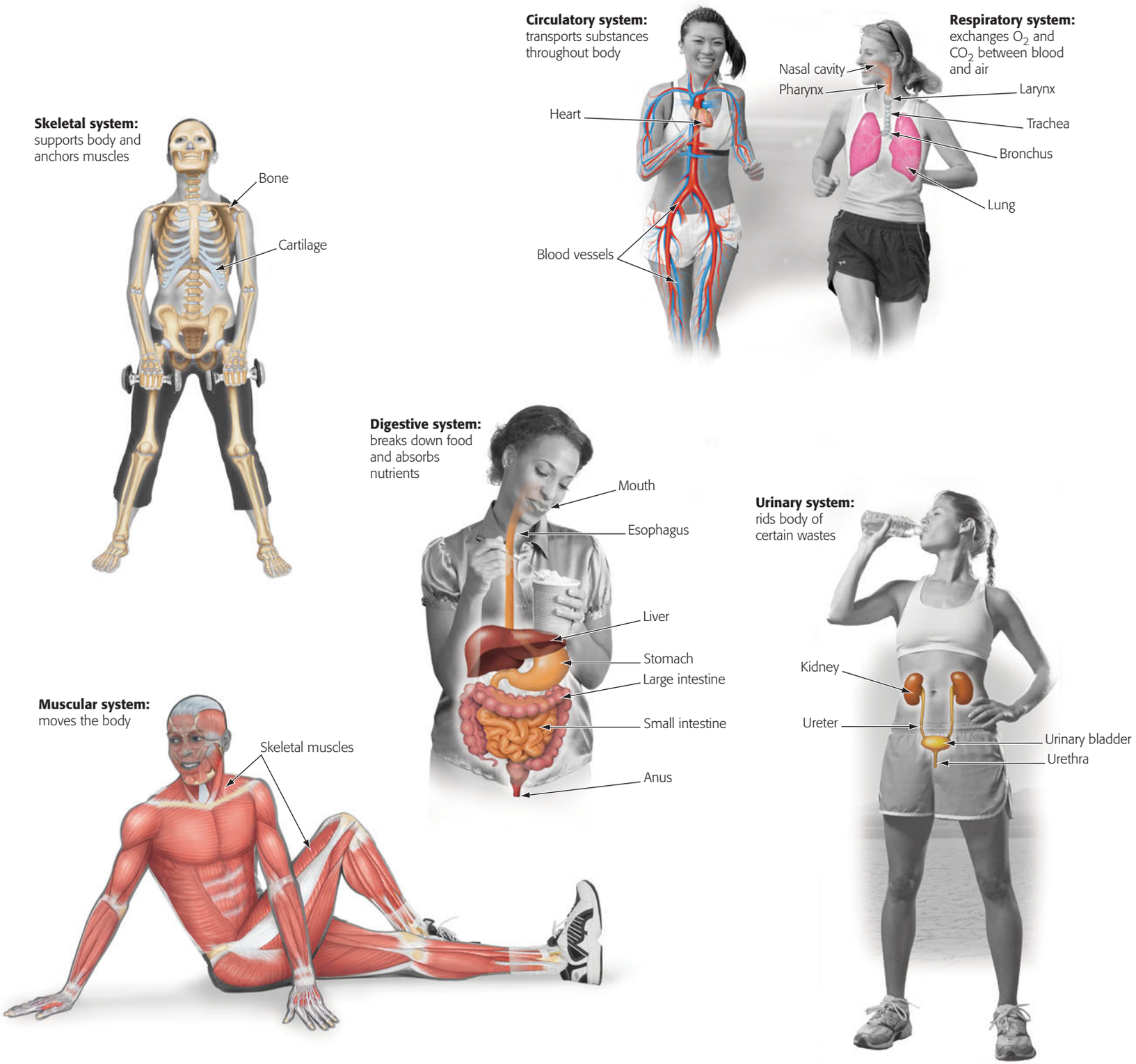
► Figure 21.7 Tissue layers of the small intestine, an organ.



The organs of humans and most other animals are organized into **organ systems**, teams of organs that work together to perform vital body functions. The components of an organ system can be physically connected or they can be dispersed within the body. An example of an organ system is your circulatory system, which transports materials throughout your body. Its main organs are the heart and blood vessels (arteries, veins, and capillaries). **Figure 21.8** presents an overview of 11 major organ systems in vertebrates.

An organism depends on the coordination of all its organ systems for survival. For instance,

▼Figure 21.8 Organ systems of a vertebrate.

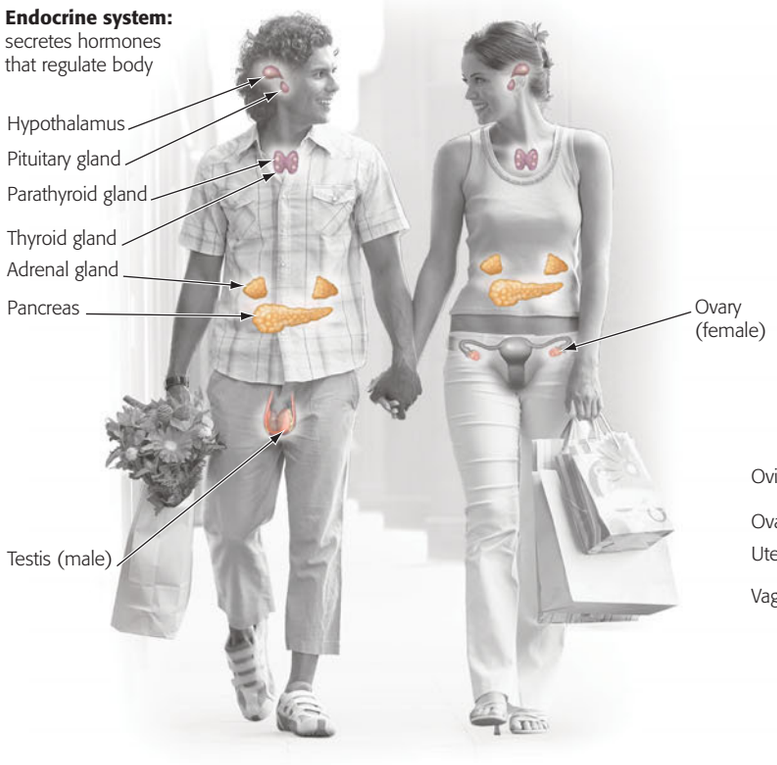


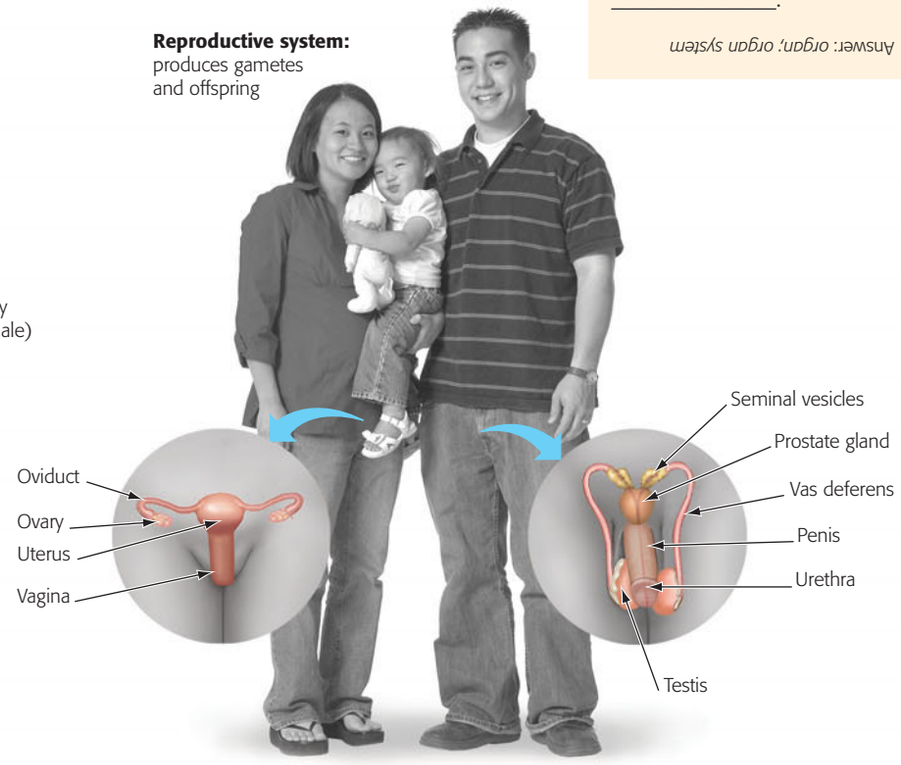
the action of muscle cells can produce body heat, raising your internal temperature. Cells within your nervous system can sense the temperature change and send signals that cause blood vessels of your circulatory system to widen, releasing heat. The failure of any organ system will jeopardize the entire animal because organ systems are so interwoven and dependent on each other. Your body is a whole, living unit that is greater than the sum of its parts. In the next section, we'll look at how the body's organ systems interact with the external environment. ☑

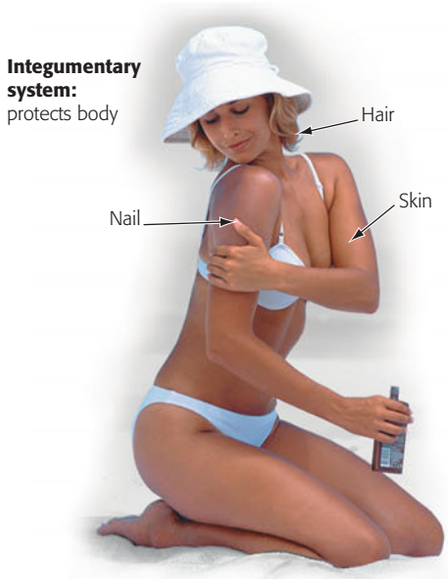
☑ CHECKPOINT

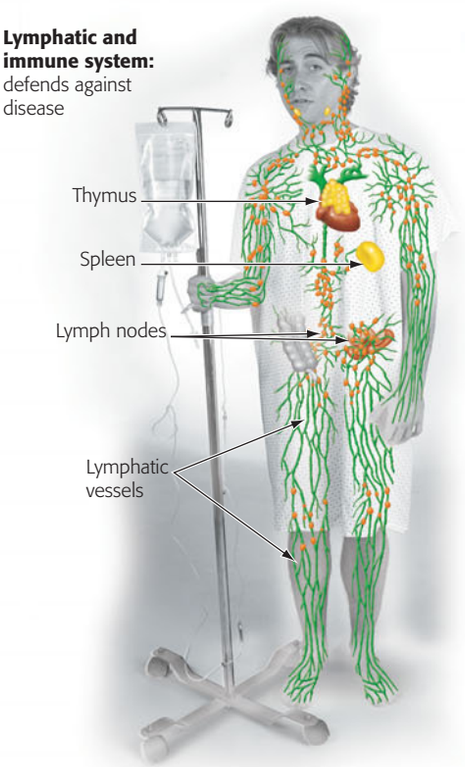
Your stomach is a(n) _____, whereas your digestive system is a(n) _____.

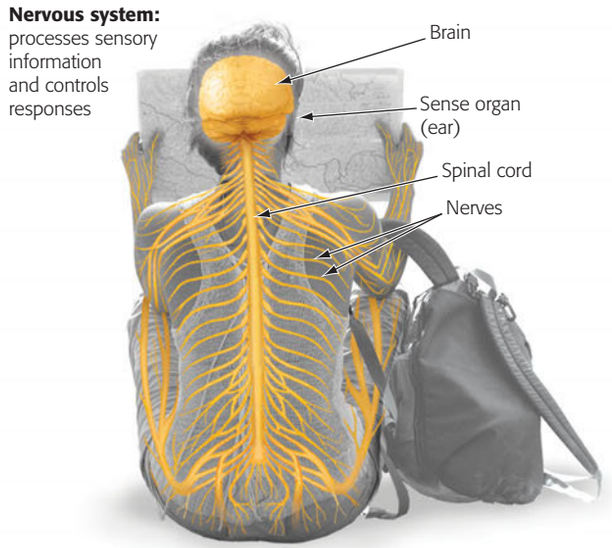
Answer: *organ; organ system*











Exchanges with the External Environment

Most animals are covered with a protective layer that separates the external world from the internal chemical environment. This does not mean, however, that an animal encloses itself in some sort of protective bubble, isolated from the harsh world outside. Just as a car engine will quickly stall if the air intake is clogged, your body will quickly shut down if deprived of outside oxygen. Every organism is an **open system** that continuously exchanges chemicals and energy with its surroundings. You eat, breathe, defecate, urinate, sweat, and radiate heat—all examples of how you operate as an open system. And the exchange of materials extends down the hierarchy to each individual cell: Nutrients and oxygen must enter every living cell, and carbon dioxide and other wastes must exit.

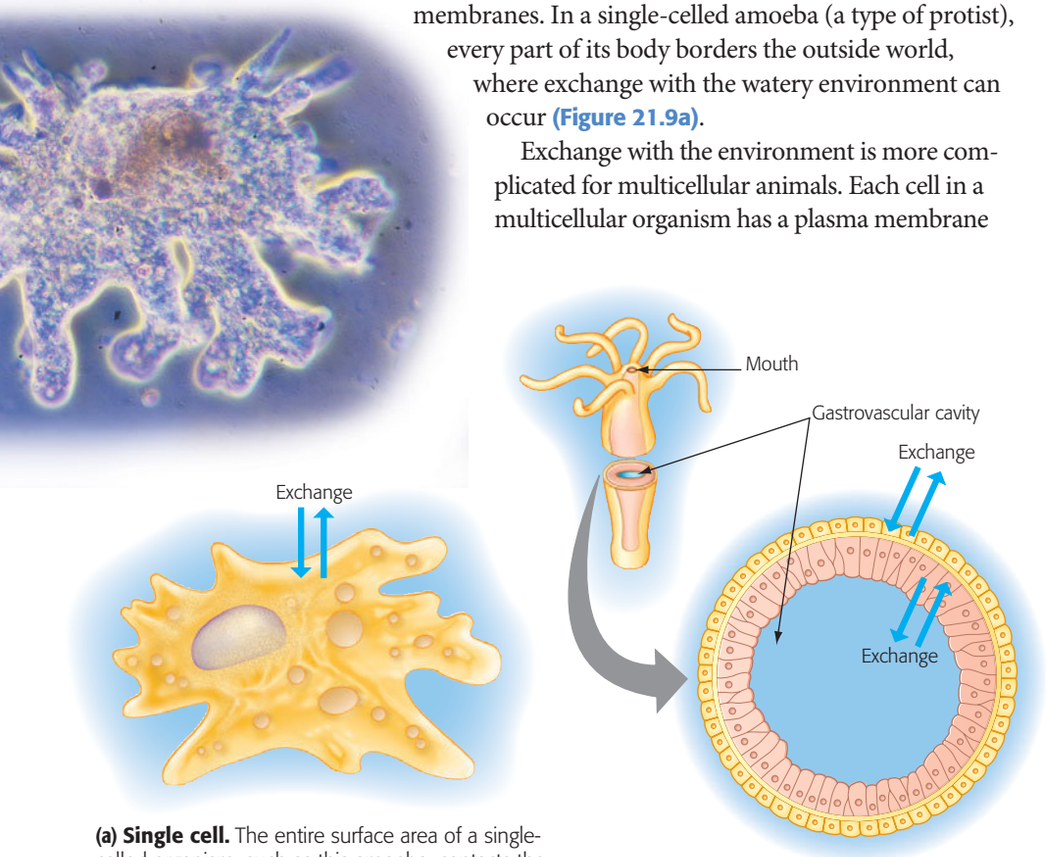
Why doesn't a parasitic tapeworm require a digestive system?

An animal's size and shape affects its exchanges with its surrounding environment. Every living cell of an animal's body must be bathed in a watery solution, partly because substances must be dissolved in water to cross cell membranes. In a single-celled amoeba (a type of protist), every part of its body borders the outside world, where exchange with the watery environment can occur **(Figure 21.9a)**.

Exchange with the environment is more complicated for multicellular animals. Each cell in a multicellular organism has a plasma membrane where exchange of materials can occur. But this exchange only works if all the cells of the animal have access to a suitable watery environment. A hydra (a simple pond-dwelling relative of jellies) has a body wall only two cell layers thick **(Figure 21.9b)**. Both layers of cells are bathed in pond water, which enters the digestive sac through the mouth. Every cell of the hydra can thus exchange materials through direct contact with the watery environment. A flat body shape is another way of maximizing exposure to the environment. For instance, a tapeworm may be several meters long, but because it is very thin, most of its cells are bathed in the body fluid of the worm's host, from which it obtains nutrients directly.

Simple body shapes do not allow for much complexity in internal organization. But animals with more complex body forms face the same basic problem: Every living cell in the body must be bathed in fluid and have access to resources from the outside environment. Complex animals have evolved extensively folded or branched internal surfaces that maximize surface area for exchange with the immediate environment. For example, your lungs, which exchange oxygen and carbon dioxide with the air you breathe, are not shaped like big balloons but like millions of tiny balloons at the tips of finely branched air tubes **(Figure 21.10)**. The epithelium of the lungs has a very large total surface area—about the size of a tennis court.

▼Figure 21.9 Contact of simple organisms with the environment.



(a) Single cell. The entire surface area of a single-celled organism, such as this amoeba, contacts the environment. Because of its small size, the organism has a large surface area (relative to its volume) through which it exchanges materials with the external world.

(b) Two cell layers. Although a hydra is multicellular, each one of its cells touches an aqueous envrionment. The body has only two cell layers, both exposed to water.

▼Figure 21.10 The branched surface area of the human lung. This plastic model shows the tiny air tubes of the lungs (white) and the thin blood vessels (red) that transport gases between the heart and lungs.

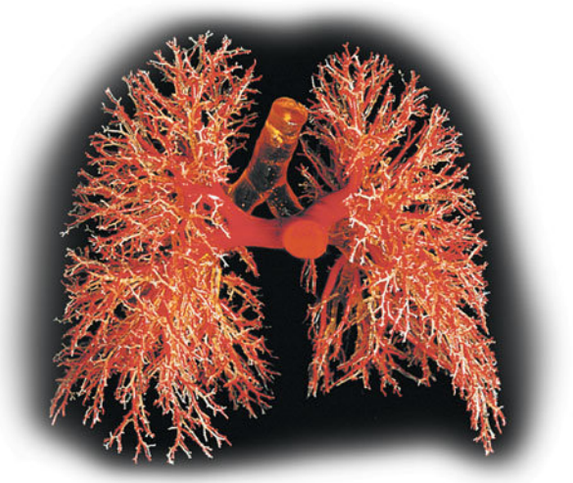
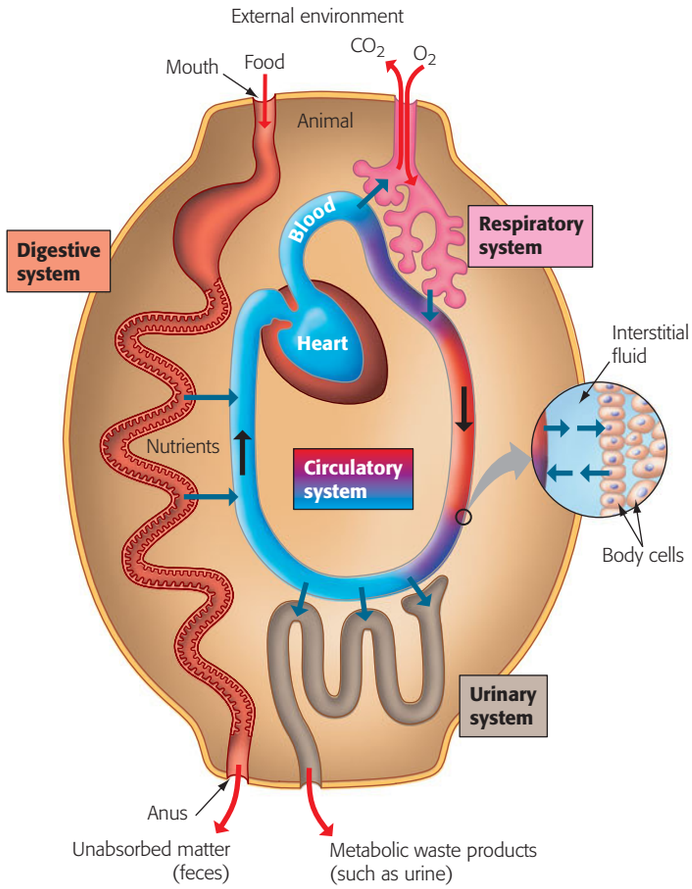


Figure 21.11 shows a schematic model of an animal body, highlighting the three organ systems—digestive, respiratory, and urinary—that exchange materials with the external environment. Notice also the vital role of the circulatory system: It connects to nearly every organ system as it transports needed materials from the environment to the body's tissues and carries wastes away. Looking at the figure, you can see how nutrients that are absorbed from the digestive tract are distributed throughout the body by the circulatory system. The heart that pumps blood through the circulatory system requires nutrients absorbed from food by the digestive tract and also oxygen (O_2) obtained from the air by the respiratory system. And absorption of nutrients inevitably produces wastes that must be excreted by the urinary system. The circulatory system thereby provides an internal conduit that joins the systems that connect with the outside world. ☑



► **Figure 21.11 Exchange between the external environment and the internal environment of complex animals.** The blue arrows indicate the exchange of materials between the circulatory system and three other systems and between the circulatory system and body cells.

☑ CHECKPOINT

Is your body an open or closed system? Why?

Answer: Your body is an open system because the digestive, respiratory, and urinary systems are in direct contact with the external environment.

Regulating the Internal Environment

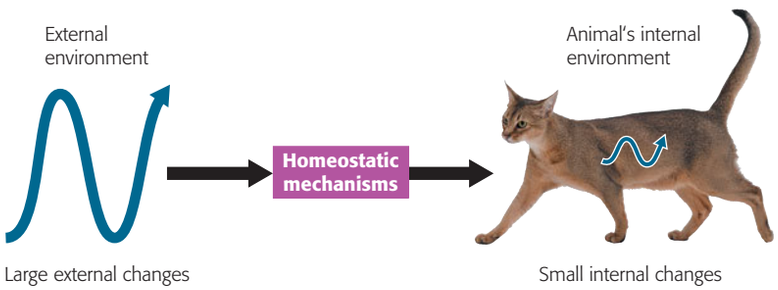
In this section, you'll learn how animals adjust to a changing environment. We'll look in particular at how they regulate temperature and control the movement of water and solutes.

Homeostasis

One of the body's most important functions is to stay relatively unchanged even when the world around it changes. The internal environment of vertebrates includes the **interstitial fluid** that fills the spaces between cells and exchanges nutrients and wastes with microscopic blood vessels (see Figure 21.11). It is important that the composition of the interstitial fluid remain relatively constant no matter what occurs in the outside world.

Homeostasis, which literally means "steady state," is the tendency to maintain relatively constant conditions in the internal environment even when the external environment changes. In the face of large external changes, the mechanisms of homeostasis normally maintain internal conditions within a range that the animal's metabolism can tolerate **(Figure 21.12)**. For example, your internal body temperature normally fluctuates by less than a degree, whether you are making an angel in the cold winter snow or a cannonball into a pool in the hot summer sun. Losing the ability to maintain homeostasis can have significant health consequences. Diabetes, for example, is a loss of glucose homeostasis in the blood.

▼ **Figure 21.12 Homeostasis.**



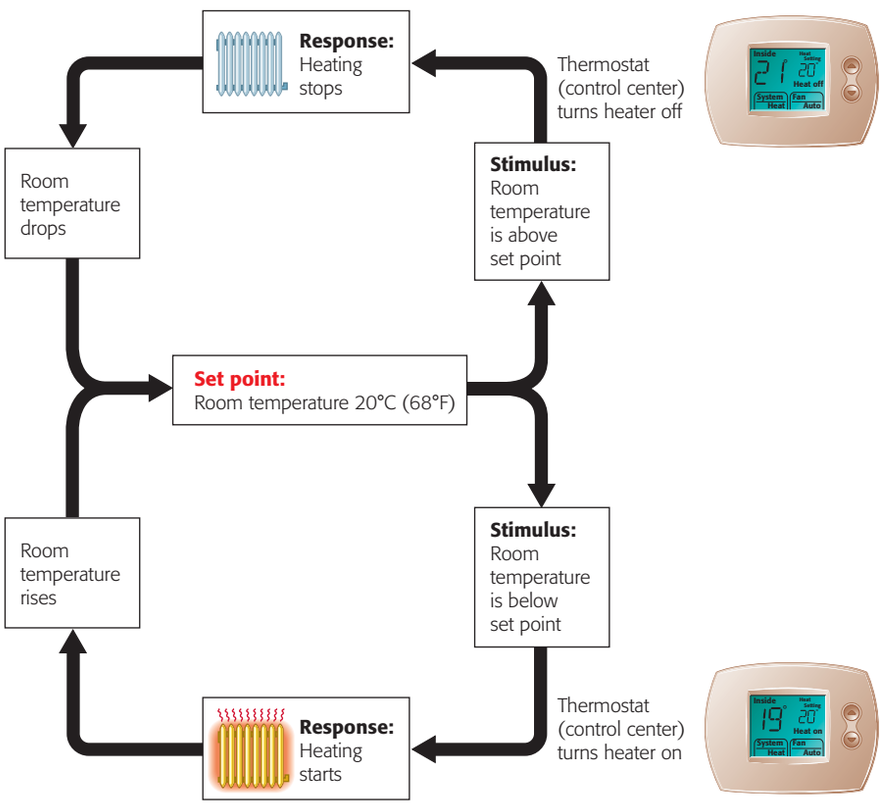
Actually, the internal environment of an animal always fluctuates slightly in response to internal and external changes. Blood glucose levels, for example, rise after a meal. Homeostasis is a dynamic state, an interplay between outside forces that tend to change the internal environment and internal control mechanisms that oppose such changes. Changes do occur, but they generally stay within a range that is tolerable for living cells. In addition, there are times during the development of an animal when major changes in the internal environment are programmed to occur. For example, the balance of hormones in human blood changes radically during puberty or pregnancy, and body temperature may rise a few degrees in response to a bacterial infection.

Negative and Positive Feedback

Most mechanisms of homeostasis depend on a principle called **negative feedback**, a form of regulation in which the results of a process inhibit that same process. Figure 21.13 illustrates the concept of negative feedback with an example of household homeostasis, the control of room temperature. During the winter, a home heating system maintains a relatively constant temperature inside the house despite drastic changes that may occur outside. A key component of this system is a control center—a thermostat—that monitors temperature and switches the heater on and off. Whenever room temperature drops below the set point (the temperature at which the thermostat is set, 20°C in the figure), the thermostat switches the heater on (bottom pathway in Figure 21.13). When the temperature rises above the set point, the thermostat switches the heater off (top pathway). The basic principle of negative feedback is simple: The result (increased room temperature, for example) of a process (heating of the air) inhibits that very process (by switching the heater off). Negative feedback is the most common mechanism of homeostatic control in animals.

Less commonly, organisms use **positive feedback**, in which the results of a process intensify that same process. For example, during the labor that leads up to childbirth, chemical signals cause the muscles of the uterus to contract. This contraction stimulates the release of more such chemicals, which cause more contractions, and so on, in a positive-feedback loop of increasing intensity. The result is climactic muscle contractions that push the baby from the womb.

In the rest of this section, we'll examine several specific examples of homeostasis. We'll first discuss the control of temperature and the control of water gain and loss in a variety of animals. We'll then focus on the human urinary system—an organ system that performs several homeostatic roles. ☑



► **Figure 21.13 An example of negative feedback: control of room temperature.** This is an example of negative feedback because the result of the process (heat) shuts that process down.

☑ CHECKPOINT

When you flush a toilet, water begins to refill the tank. The rising water level lifts a float. When the float reaches a certain height, it stops more water from entering the tank. This is an example of what kind of homeostatic control? Why?

Answer: This is an example of negative feedback because the result of a process (water filling the tank) inhibits that same process.

Thermoregulation

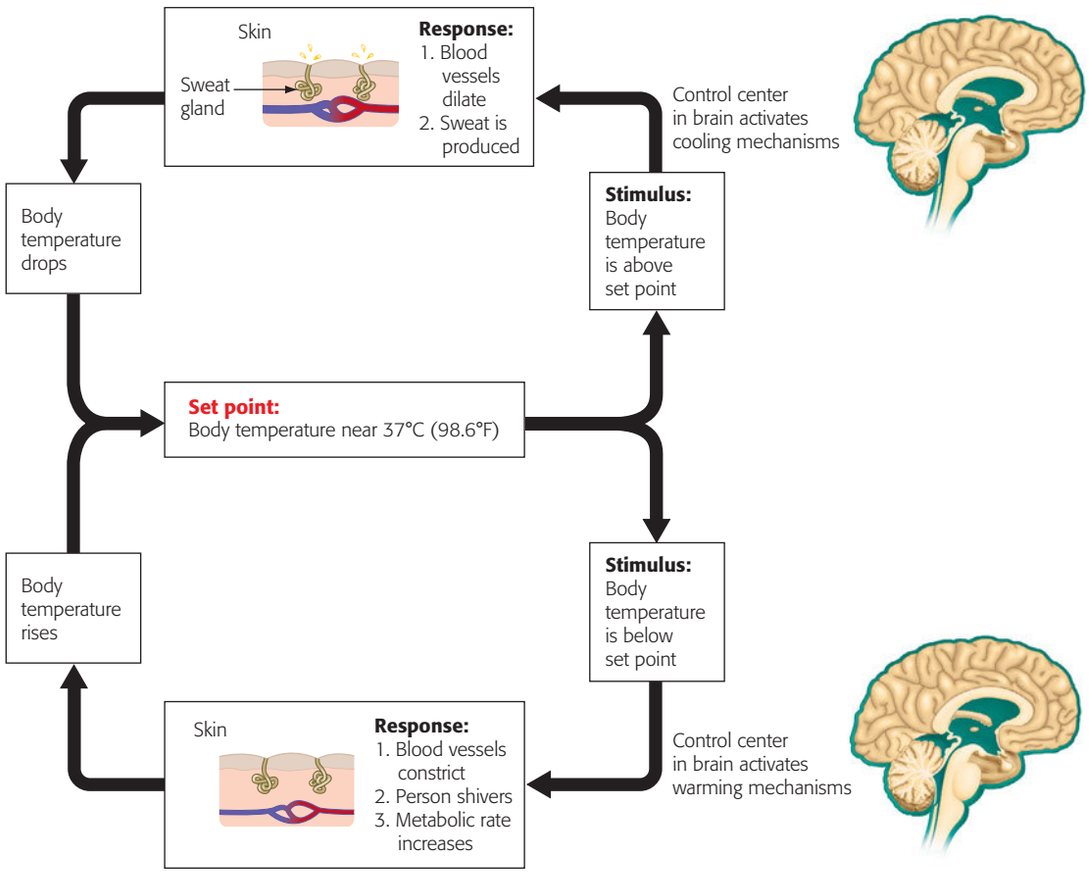
As you saw in the Biology and Society section, the maintenance of internal body temperature is important in animals. This homeostatic mechanism is called **thermoregulation**. As you walk from a warm building to the outside on a cold winter day, your body's temperature will barely fluctuate, despite the drastic change in temperature in the environment around you. The ability to maintain a body temperature substantially warmer than the surrounding environment is characteristic of **endotherms**, animals such as mammals and birds that derive most of their body heat from their own metabolism. In contrast, **ectotherms**, which include most invertebrates, fishes, amphibians, and nonbird reptiles, obtain their body heat primarily by absorbing it from their surroundings.

You have a number of structures and mechanisms that aid in thermoregulation. As shown in **Figure 21.14**, your brain has a control center that maintains your body temperature near 37°C (98.6°F). When your body temperature falls below normal, your brain's control center sends signals that trigger changes that will bring it back to normal: Blood vessels near your body's surface constrict (conserving heat) and muscles contract, causing you to shiver (producing heat). When body temperature gets too high, the control center sends signals to dilate the blood vessels near your skin and activate sweat glands, allowing excess heat to escape. Like a home controlled by a thermostat, the temperature of the body does not stay completely constant but fluctuates up and down within an acceptable range.

Why do you shiver when you are cold?

Fever, an abnormally high internal temperature, is a body-wide response that usually indicates an ongoing fight against infection. When your immune system cells encounter invading microbes, the cells release chemicals that travel through the bloodstream to your brain. These chemicals stimulate your brain's thermostatic control center to raise the body's internal temperature, producing a fever. Many people mistakenly believe that the invading microbes themselves cause a fever. In fact, the cause is usually the body's fight *against* the microbes. A fever of more than 40°C (104°F) may be life-threatening because a temperature that high can damage body proteins. A moderate fever of 38–39°C (100–102°F), however, discourages bacterial growth and speeds the body's internal defenses. A moderate fever thus helps protect the body's internal environment against potentially harmful invaders from the external environment.

We are endotherms and so can generate body heat to warm ourselves. Ectotherms generally cannot. But there are exceptions to this rule, as we'll see next in the Process of Science section. ☑



◄ Figure 21.14
Thermoregulation in the human body. By comparing this figure with Figure 21.13, you can see how similar negative-feedback controls moderate the temperatures of a room and your body. The control center for body temperature is located in the brain.

☑ CHECKPOINT

Name two features of the human body that help release heat and two features that help keep the body warm.

Answer: Examples include sweating and dilation of blood vessels to release heat; shivering and constriction of blood vessels to keep the body warm.



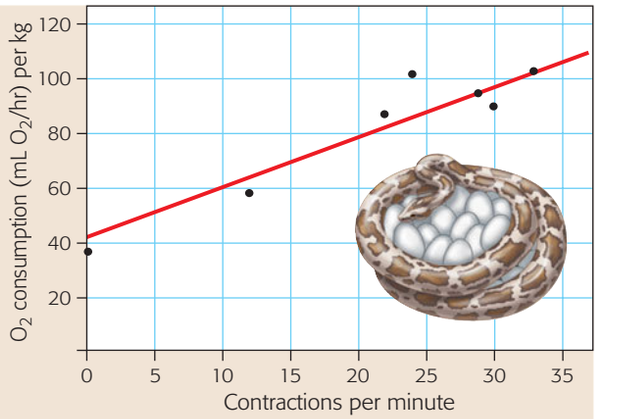
Controlling Body Temperature THE PROCESS OF SCIENCE

How Does a Python Warm Her Eggs?

As just described, ectotherms usually absorb heat from their surroundings. Under certain circumstances, however, some ectotherms can generate their own body heat. An example is the Burmese python (*Python molurus bivittatus*), a very large snake native to the rain forests of southeastern Asia. Like most snakes, it reproduces by laying eggs. Researchers at the Bronx Zoo, in New York City, made the **observation** that a female Burmese python incubating her eggs wraps her body around them, raises her body temperature, and frequently contracts the muscles in her coils. They formed the **hypothesis** that the muscle contractions elevate the snake's body temperature.

To test their hypothesis, they performed a simple **experiment**. They placed a python and her eggs in a chamber. As they varied the chamber's temperature, they monitored the python's muscle contractions and oxygen uptake, a measure of her rate of cellular respiration. Their **results** showed that the python's oxygen consumption increased when the temperature in the chamber decreased. Her oxygen consumption also changed with the rate of muscle contraction (Figure 21.15). Because oxygen consumption generates heat through cellular respiration and increases with the rate of muscle contraction, the researchers concluded that the muscle contractions were the source of the Burmese python's elevated body temperature during egg incubation. As you'll see in the Evolution Connection section, such behavior is just one of many temperature-regulating adaptations that have evolved in animals.

▼ **Figure 21.15 Oxygen consumed by a Burmese python as it constricts its muscles.**



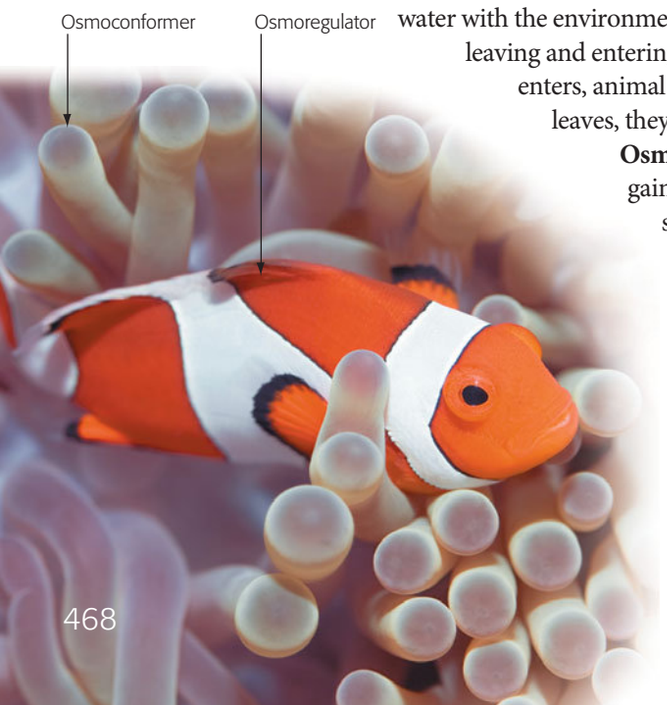
Osmoregulation

Living cells depend on a precise balance of water and solutes (dissolved substances). Whether an animal inhabits land, fresh water, or salt water, its cells cannot survive if too much water enters or leaves. That is, a cell may exchange water with the environment as long as the total amount leaving and entering is the same. If too much water enters, animal cells will burst; if too much leaves, they will shrivel and die.

Osmoregulation is the control of the gain or loss of water and dissolved solutes, such as the ions of NaCl and other salts. Osmoregulation is based largely on regulating solutes because water follows the movement of solutes by osmosis. Osmosis occurs whenever two solutions separated by a permeable membrane differ in their total solute concentrations (see Figure 5.13). There is always a net movement of water from the solution with lower solute concentration to the one with higher solute concentration.

A variety of mechanisms have evolved that maintain water balance in aquatic animals. Most marine invertebrates—such as lobsters, scallops, and jellies—are **osmoconformers**, meaning that their internal and external environments have similar solute concentrations. Osmoconformers do not need special mechanisms to prevent a net gain or loss of water. In contrast, all freshwater animals and most of the marine vertebrates are **osmoregulators**: They must actively regulate water loss and gain (Figure 21.16).

As an example, let's compare osmoregulation in freshwater and saltwater fish. Both kinds of fish have about the same concentration of solutes in their blood despite their very different environments: Saltwater fish have less salt in their tissues than the water they swim in, while freshwater fish have more. How do they achieve this control? In fresh water, the external solute concentration is low, so water enters the fish



◄ **Figure 21.16 Osmoconformers and osmoregulators.** Most marine invertebrates (such as the sea anemone whose tentacles are visible here) are osmoconformers, which have water concentrations similar to their surroundings. Most marine vertebrates (such as this clown fish) are osmoregulators, which use mechanisms to maintain water balance.

by osmosis. To compensate, freshwater fish take up solutes via the digestive system and gills and produce large amounts of dilute urine. In contrast, osmoregulators that live in salt water lose water by osmosis. In response, saltwater fish take in water by drinking, pump out ions via the gills, and produce only small amounts of concentrated urine.

All land animals are osmoregulators. Most land animals gain water from eating and drinking and lose it through urinating, defecating, breathing, and perspiring. The primary challenge facing land-dwelling osmoregulators is to avoid becoming dehydrated. As we'll see in the next section, our kidneys play a major role in regulating water balance. ☑

Homeostasis in the Urinary System

The human urinary system plays a central role in forming and excreting waste-carrying urine while regulating the amount of water and solutes in body fluids. The main processing centers are the two kidneys. Each is a compact organ, a bit smaller than a fist, located on either side of the abdomen. The kidneys contain nearly 100 miles of thin tubes called **tubules** and an intricate network of capillaries (tiny blood vessels). Every day, all of your blood passes through the capillaries of your kidneys hundreds of times. As the blood circulates, a fraction of it is filtered, and the plasma (the liquid portion) enters the kidney tubules. Once there, the plasma is called **filtrate**. The filtrate contains valuable substances that need to be reclaimed (such as water and glucose) and other substances that need to be disposed of. Chief among the waste products to be excreted is urea, a nitrogen-containing compound produced from the breakdown of proteins and nucleic acids. Humans must dispose of urea, but we cannot simply excrete all of the filtrate as urine; if we did, we would lose vital nutrients and dehydrate rapidly. Instead, our kidneys refine the filtrate, concentrating the wastes and returning most of the water and useful solutes to the blood.

The anatomy of the human urinary system is shown in Figure 21.17. Starting with the whole system in **Figure 21.17a**, blood to be filtered enters each kidney via a blood vessel called the renal artery. Filtered blood leaves the kidney in the renal vein. **Figure 21.17b** shows a cutaway view of a kidney. Within the kidney, the renal artery branches into millions of thin blood vessels. **Figure 21.17c** shows one branch of the renal artery supplying blood to a nephron via a network of capillaries. A **nephron** consists of a tubule and its associated blood vessels. Each kidney contains about a million nephrons.

The nephrons carry out the functions of the urinary system. Blood pressure forces water and solutes from the blood through a filter at the start of the nephron tubule, creating filtrate. As the filtrate then passes through the tubule, water and needed nutrients are reabsorbed into the bloodstream and wastes are secreted into the filtrate. The filtrate becomes more and more concentrated, resulting in a relatively small quantity of **urine**. At the end of the tubule, urine leaves the nephron via a collecting duct. Urine collects in the kidney and then leaves via the **ureter**. Urine is stored in the **urinary bladder** (visible in Figure 21.17a). Periodically, urine is expelled from the urinary bladder via the **urethra**, a tube that empties near the vagina in females and through the penis in males.

☑ CHECKPOINT

Name two ways that water enters your body and four ways that water leaves your body.

Answer: Water enters via eating and drinking and leaves via breathing, sweating, urinating, and defecating.

▼Figure 21.17 Anatomy of the human urinary system.

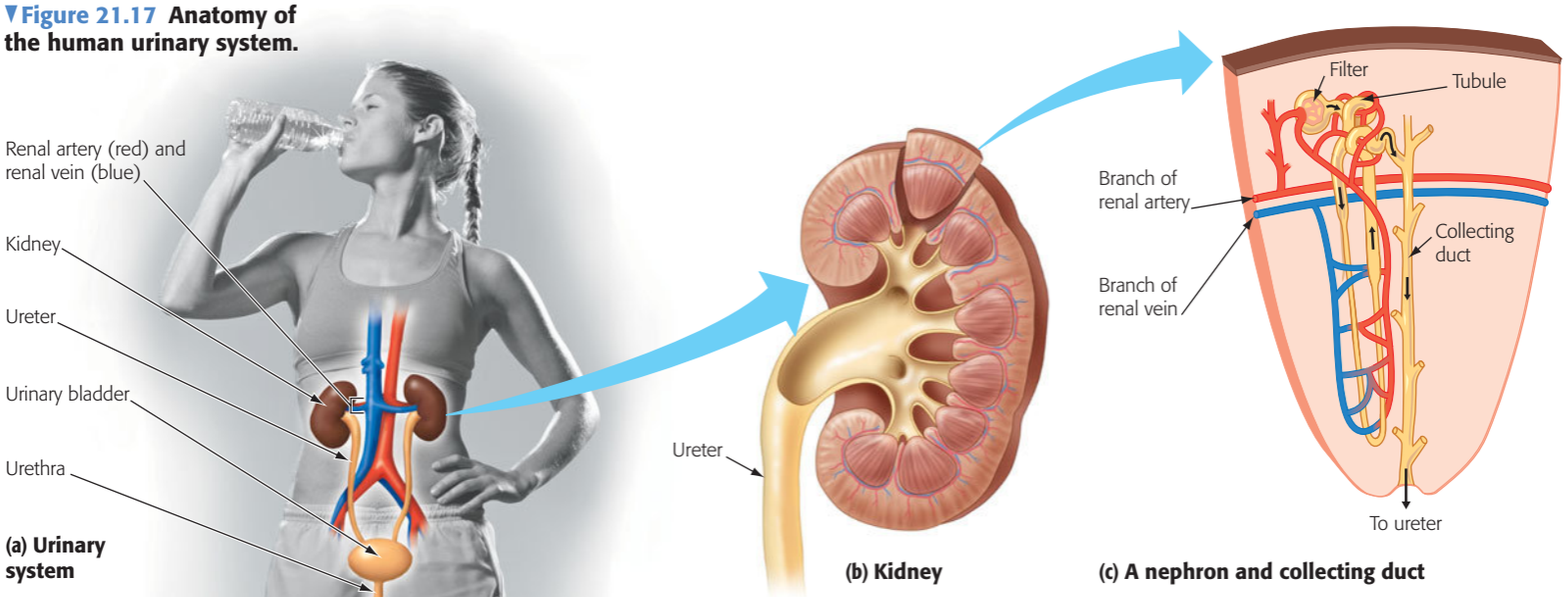


Figure 21.18 summarizes the functions performed by each nephron. First, during **filtration**, water and other small molecules are forced from the blood through a capillary wall into the beginning of a kidney tubule, forming filtrate. Next, in **reabsorption**, water and valuable solutes are reclaimed from the filtrate and returned to the blood. In **secretion**, certain substances, such as some ions and drugs, are transported into the filtrate. What remains after filtration, reabsorption, and secretion is the urine. Finally, in **excretion**, urine passes from the kidneys to the outside.

Why is kidney failure inevitably fatal if untreated?

The body controls its concentration of water and dissolved molecules through hormones that act on the kidney's nephrons. When the solute concentration of body fluids rises too high (indicating that not enough water is present), the brain increases levels of a hormone called ADH (antidiuretic hormone) in the blood. This hormone signals the nephrons to reabsorb more water from the filtrate, effectively increasing the body's water content. Conversely, when body fluids become too dilute, blood levels of ADH drop, the kidneys reabsorb less water, and the excreted urine becomes much more dilute. This is why your urine is very clear after you have been drinking a lot of water. Diuretics, such as alcohol, are substances that inhibit the release of ADH and therefore cause excessive urinary water loss. Drinking alcohol will make you urinate more frequently, and the resulting dehydration contributes to the symptoms of a hangover.

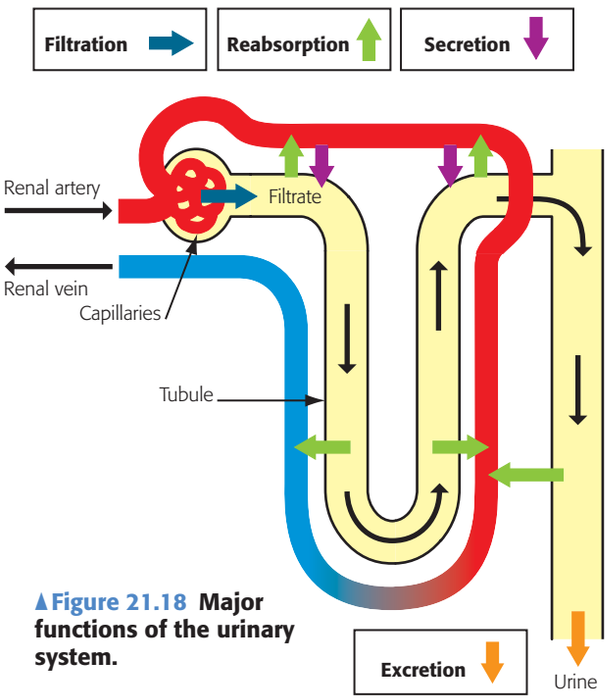
Kidney failure, the inability of the kidneys to filter blood, can be caused by injury, illness (such as high blood pressure or diabetes), or prolonged use of pain relievers (including over-the-counter medicines such as aspirin), alcohol, or other drugs. If the kidneys fail, the body is unable to rid itself of wastes. A person with one functioning kidney can lead a normal life, but if both kidneys fail, the buildup of toxic wastes will lead to certain and rapid death. One option is to place the person on **dialysis**, filtration of the blood by a machine that mimics the action of a nephron **(Figure 21.19)**. Blood from an artery enters a series of selectively permeable tubes. Urea and excess fluids pass from the blood into a dialyzing solution, while necessary salts and other substances transfer the opposite way. The machine discards the used dialyzing solution as wastes accumulate. Dialysis treatment is life sustaining for people with kidney failure, but it is costly, takes a lot of time (about 4–6 hours three times a week), and must be continued for life. Alternatively, a kidney from a living compatible donor (usually a relative) or a deceased organ donor can be transplanted into a person with kidney failure. Unfortunately, the number of people who need kidneys is much greater than the number of kidneys available, and the average wait for a kidney donation in the United States is three to five years.

Throughout our study of animal form and function in this unit, you will see many other examples of how mechanisms of homeostasis moderate changes in the internal environment despite larger fluctuations in the external environment. You will also see many other examples of what happens when homeostatic controls fail. ☑

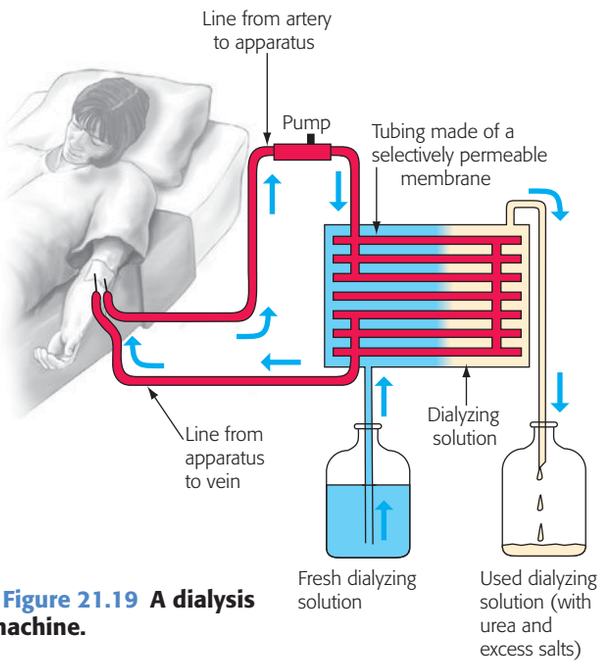
☑ CHECKPOINT

Name the four processes that occur as kidney tubules process blood and create urine.

Answer: *filtration, reabsorption, secretion, excretion*



▲Figure 21.18 Major functions of the urinary system.



▲Figure 21.19 A dialysis machine.



Controlling Body Temperature EVOLUTION CONNECTION

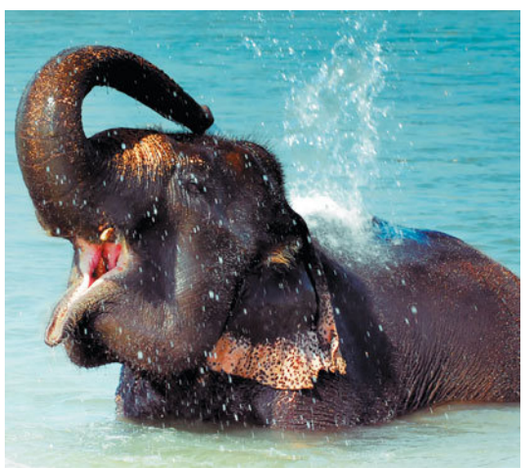
Adaptations for Thermoregulation

Natural selection has promoted a wide variety of adaptations—anatomical, physiological, and behavioral—that help animals cope with heat gained from or lost to the environment **(Figure 21.20)**. A major anatomical adaptation in mammals and birds is insulation, consisting of hair (often called fur), feathers, or fat layers. A thin coat of fur in the summer often becomes a thick, insulating coat during the winter. Also, most land mammals and birds react to cold by raising their fur or feathers; this adaptation traps a thicker layer of air next to the warm skin, improving the insulation. In people, our muscles raise our hair in the cold, causing goose bumps, a vestige from our furry ancestors. Aquatic mammals (such as seals) and aquatic birds (such as penguins) have a thick insulating layer of fat called blubber.

Some adaptations are physiological. In cold weather, hormonal changes tend to boost the metabolic rate of birds and mammals, increasing their heat production. Simply moving around more or shivering also produces heat as a metabolic by-product of the contraction of skeletal muscles. Honeybees survive cold winters by clustering together and shivering in their hive. Their metabolic activity generates enough heat to keep the cluster alive. Panting and sweating are examples of physiological adaptations that greatly increase cooling.

A variety of behavioral responses can regulate body temperature. Some birds and butterflies migrate seasonally to more suitable climates. Other animals, such as desert lizards, bask in the sun when it is cold and find cool, damp areas or burrows when it is hot. Honeybees cool their hive during hot weather by transporting water into it and fanning with their wings. Many animals cool themselves by bathing, and a few even spread saliva on their bodies. Some mammals, such as ground squirrels and chipmunks, drastically reduce their body temperature and metabolic rate by hibernating in burrows during the winter, thereby conserving energy. All of these mechanisms—anatomical, physiological, and behavioral—demonstrate how a single selection pressure (the need to thermoregulate) can drive the evolution of a multitude of adaptations in a wide variety of environments.

▼Figure 21.20 Methods of thermoregulation in animals.

METHODS OF THERMOREGULATION		
Anatomical Adaptations (such as hair, fat, and feathers)	**Physiological Adaptations** (such as panting, shivering, and sweating)	**Behavioral Adaptations** (such as bathing, basking, hibernating, and migrating)
	 Panting	 Bathing

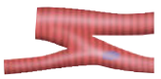
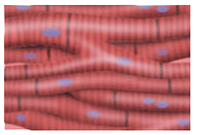
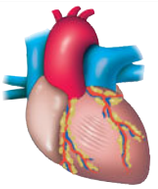
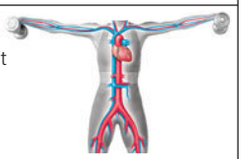
Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

The Structural Organization of Animals

HIERARCHICAL ORGANIZATION OF ANIMALS

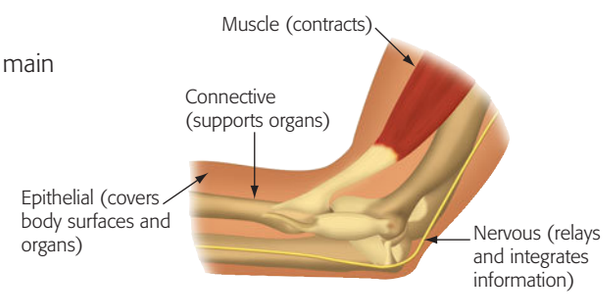
Level	Description	Example
Cell	The basic unit of all living organisms	 Muscle cell
Tissue	A collection of similar cells performing a specific function	 Cardiac muscle
Organ	Multiple tissues forming a structure that performs a specific function	 Heart
Organ system	A team of organs that work together	 Circulatory system
Organism	A living being, which depends on the coordination of all structural levels for homeostasis and survival	 Person

Form Fits Function

At every level, the structure of a body part is correlated with the task it must perform. Anatomy is the study of the structure of organisms, whereas physiology is the study of the function of an organism's structures.

Tissues

Animals have four main kinds of tissue.



Organs and Organ Systems

An organ is a collection of tissues that together perform a specific function; an organ system is a group of organs that together provide a vital function for the organism. Figure 21.8 summarizes the 11 major human organ systems.

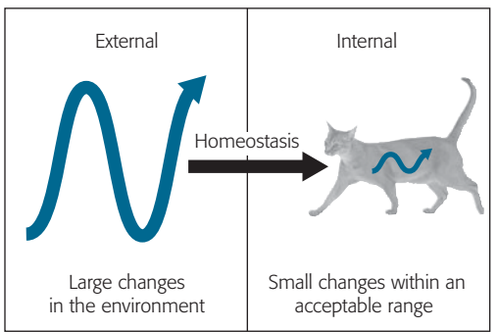
Exchanges with the External Environment

All animals are open systems, exchanging chemicals and energy with the environment. Every cell of a simple organism can exchange materials through direct contact with the environment. Large and complex body shapes require indirect exchange between extensively branched internal structures and the environment, usually via a circulatory system.

Regulating the Internal Environment

Homeostasis

Homeostasis is the body's tendency to maintain relatively constant internal conditions despite large fluctuations in the external environment.



Negative and Positive Feedback

In negative feedback, the most common homeostatic mechanism, the results of a process inhibit that process. Less common is positive feedback, in which the results of a process amplify that process.

Thermoregulation

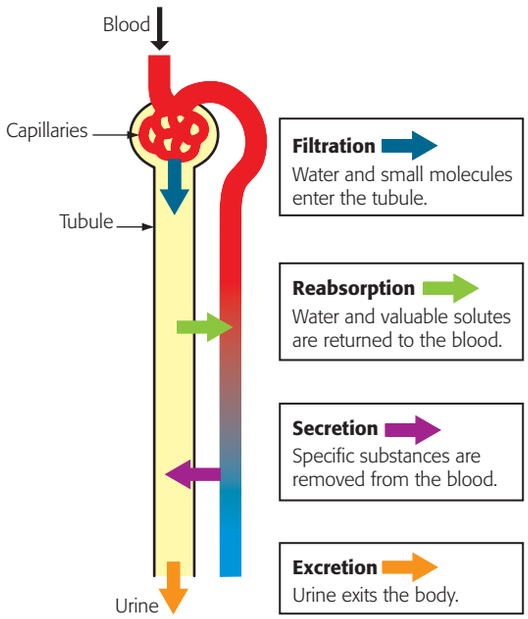
In thermoregulation, homeostatic mechanisms regulate internal body temperature. Endotherms are warmed primarily by heat generated during metabolism. Ectotherms are warmed primarily by heat absorbed from the environment.

Osmoregulation

All organisms balance the gain or loss of water and dissolved solutes. Osmoconformers do not tend to undergo a net gain or loss of water because their internal and external environments have similar solute concentrations. In contrast, osmoregulators must actively regulate their water balance—by drinking and urinating, for example.

Homeostasis in the Urinary System

The urinary system expels wastes and regulates solute and water balance. The following diagram summarizes the structure and function of the nephron, the functional unit of the kidney.



SELF-QUIZ

1. List as many units of structural hierarchy in your body as you can, in order from smallest to largest.
2. How might body shape affect whether an animal requires a circulatory system?
3. Which of the following best illustrates homeostasis?
   a. Most adult human beings are between 5 and 6 feet tall.
   b. The lungs and intestines have large surface areas for exchange.
   c. When the concentration of water in the blood goes up, the kidneys expel more water.
   d. When oxygen in the blood decreases, you may feel light-headed.
4. Most human cells are surrounded by an aqueous solution called _____.
5. Stimulation of a nerve cell causes sodium ions to leak into the cell, and the sodium influx triggers the inward leaking of even more sodium. This is an example of _____ feedback. An increase in the concentration of glucose in the blood stimulates the pancreas to secrete insulin, a hormone that lowers blood glucose concentrations. This is an example of _____ feedback.
6. What is the main difference between endotherms and ectotherms?
7. Like most vertebrates, you are a(n) _____; your body must actively regulate the gain or loss of water. In contrast, a lobster is a(n) _____, living in an environment with a solute concentration similar to that of its body.
8. Which of the following is not one of the homeostatic functions of the kidney?
   a. reabsorption
   b. filtration
   c. excretion
   d. ingestion
9. Drinking alcohol makes you urinate more frequently because
   a. alcohol contains caffeine.
   b. alcohol inhibits the release of ADH, a hormone that increases water reabsorption in the kidneys.
   c. alcohol inhibits the release of ADH, a hormone that decreases water reabsorption in the kidneys.
   d. alcohol causes more water to filter from the blood into the kidneys.
10. What happens to most of the water that passes from the blood into the kidneys by filtration? What happens to the rest of it?

Answers to these questions can be found in Appendix: Self-Quiz Answers.

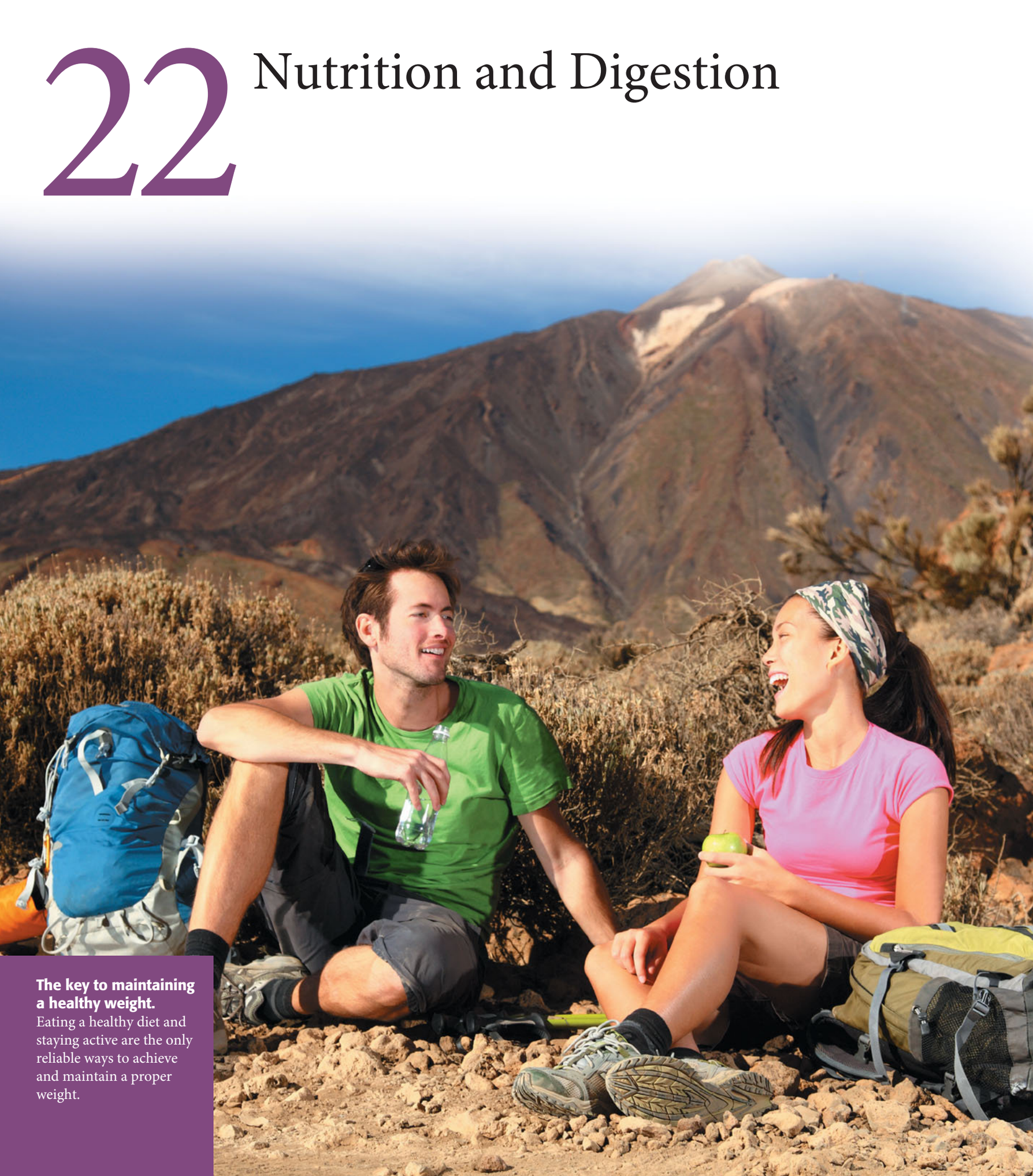
THE PROCESS OF SCIENCE

11. Eastern tent caterpillars (*Malacosoma americanum*) live in sizable groups in silk nests, or tents, typically in cherry and apple trees. They emerge early in the spring, when daily temperatures fluctuate from freezing to hot. Early in the morning, these black caterpillars rest in a tightly packed group on the east-facing surface of the tent. In midafternoon, the group is found on the tent undersurface, each caterpillar hanging from the tent by a few of its legs. Propose a hypothesis to explain this behavior. How could you test it?

BIOLOGY AND SOCIETY

12. The kidneys remove many drugs from the blood, and these substances show up in the urine. Some employers require a urine drug test at the time of hiring and/or at intervals during employment. Should an employee have the right to refuse a urine test? Should every job be subject to mandatory drug testing? If not, which jobs should be subject to testing? Would you take a drug test for a job? Why or why not?
13. Kidneys were the first organs to be successfully transplanted. A donor can live a normal life with a single kidney, making it possible for individuals to donate a kidney to an ailing relative or even an unrelated individual. Should a person be allowed to sell a kidney? Why or why not? What are some ethical issues raised by organ commerce?

22 Nutrition and Digestion



The key to maintaining a healthy weight. Eating a healthy diet and staying active are the only reliable ways to achieve and maintain a proper weight.



CHAPTER CONTENTS

Overview of Animal Nutrition 476
A Tour of the Human Digestive System 479
Human Nutritional Requirements 485
Nutritional Disorders 489

CHAPTER THREAD
Controlling Your Weight

BIOLOGY AND SOCIETY
The "Secret" to Shedding Pounds 475
THE PROCESS OF SCIENCE
Can a Gene Make You Fat? 490
EVOLUTION CONNECTION
Fat and Sugar Cravings 491



Controlling Your Weight BIOLOGY AND SOCIETY

The "Secret" to Shedding Pounds

Americans are obsessed with weight. About 50 million Americans (one in seven) go on a diet each year. Weight loss is a growth industry, with the leading weight loss programs boasting millions of members. Although Americans spend billions of dollars each year on diets and related products, only about 5% of dieters are able to reach their goal weight and maintain it for the long term.

For many of us, the obsession with weight loss is understandable. More than a third of American adults are obese (very overweight), and obesity is estimated to contribute to 300,000 deaths per year in the United States through increased incidence of heart disease, diabetes, cancer, and other health problems. Young adults are often particularly susceptible to sudden weight gain because the switch to independent living in college can lead to changes in diet and activity levels, often for the worse. And the problem is not limited to the United States: The United Nations World Health Organization recognizes obesity as a major global health problem. For most of us, therefore, it is healthy and proper to put effort into controlling our weight.

But with the wealth of fad diets with bogus claims, it can be difficult for you to know the best way to shed pounds. The good news is that there really is no trick to managing your weight: Add up the calories from the food you eat and then subtract the calories that your body burns. If you take in more by eating than you burn by activity, you will gain weight. If you burn more than you take in, you will lose weight. Weight control can be summed up in a five-word "secret": Eat less and exercise more! This is easier said than done, but the principle is sound and simple.

Caloric balance alone does not ensure good nutrition. Food must also provide the raw materials from which you build your body. You are what you eat: Your health and appearance depend on the quality of your diet and the proper functioning of your digestive system. This chapter focuses on essential concepts of digestion and nutrition, beginning with an overview of how animals process food. Next, we'll focus on the structure and function of the human digestive system. Along the way, we'll come back to the topic of weight loss as a reminder of the importance of this topic.

Overview of Animal Nutrition

Every mealtime reminds us that we must eat other organisms to acquire organic nutrients. Food provides the raw materials that animals, including people, need to build tissue and fuel cellular work. However, food primarily consists of large, complex molecules that are not in a form an animal's cells can use. Thus, the body must break down these nutrients—digest them—to make them useful.

Animal Diets

All animals eat other organisms, dead or alive, whole or by the piece. Beyond that generalization, however, animal diets vary extensively (Figure 22.1). **Herbivores**, such as cattle, gorillas, and sea urchins, feed mainly on plants or algae. **Carnivores**, such as lions, snakes, and spiders, mainly eat other animals. **Omnivores**, such as crows, cockroaches, and people, regularly eat animals as well as plants or algae. ☑

☑ CHECKPOINT

A chicken eats corn and bugs. That makes it a(n) _____.

Answer: *omnivore*

The Four Stages of Food Processing

Think of the fate of one of your meals—such as a slice of pizza—and you'll start to get a sense of the four stages of food processing: ingestion, digestion, absorption, and elimination. **Ingestion** is just another word for eating. You ingest pizza when you bite off a piece. **Digestion** is the breakdown of food into molecules small enough for the body to absorb. The tomato sauce on a pizza, for example, is broken down to simple sugars and amino acids. **Absorption** is the uptake of the small nutrient molecules by cells. For instance, amino acids made available by the breakdown of the cheese protein in pizza are absorbed by cells lining the small intestine and transferred to the bloodstream, which distributes them throughout the body. **Elimination** is the disposal of undigested materials left over from food.

▼ **Figure 22.1 Animal diets.** Animals can be classified into three broad groups according to their diet.

ANIMAL DIETS

Herbivore (mainly eats plants or algae)	**Carnivore** (mainly eats animals)	**Omnivore** (regularly eats animals as well as plants or algae)
		

Digestion: A Closer Look

Digestion usually begins with physical processes such as chewing. Such mechanical digestion breaks chunks of food into small pieces, exposing them to chemical digestion, the breakdown of food by digestive enzymes. Food molecules that are polymers, such as carbohydrates and proteins, are broken down via chemical digestion into monomers (see Chapter 3). For instance, starch is digested to its component glucose monomers.

The dismantling of food molecules is necessary for two reasons. First, these molecules are too large to cross the membranes of animal cells; they must be broken down into molecules that are small enough for cells to absorb. Second, most food molecules—the proteins in cheese, for example—are different from the molecules that make up an animal's body. Your body does not directly use the protein that you eat but instead dismantles it and uses the pieces (amino acids) to build its own new proteins **(Figure 22.2)**.

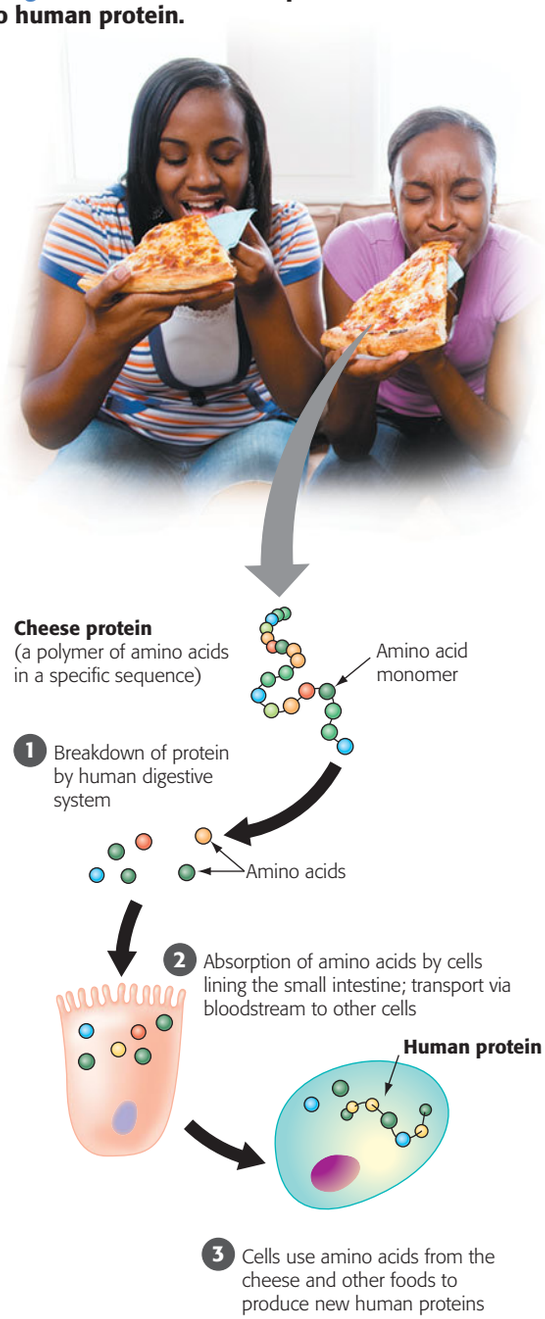
Chemical digestion happens via hydrolysis, chemical reactions that break down large biological molecules by the addition of water molecules (see Figure 3.4b). Like most of life's chemical reactions, digestion requires enzymes **(Figure 22.3)**. For example, lipases are enzymes that digest fats, such as those found in pizza's cheese and meat. ☑

☑ CHECKPOINT

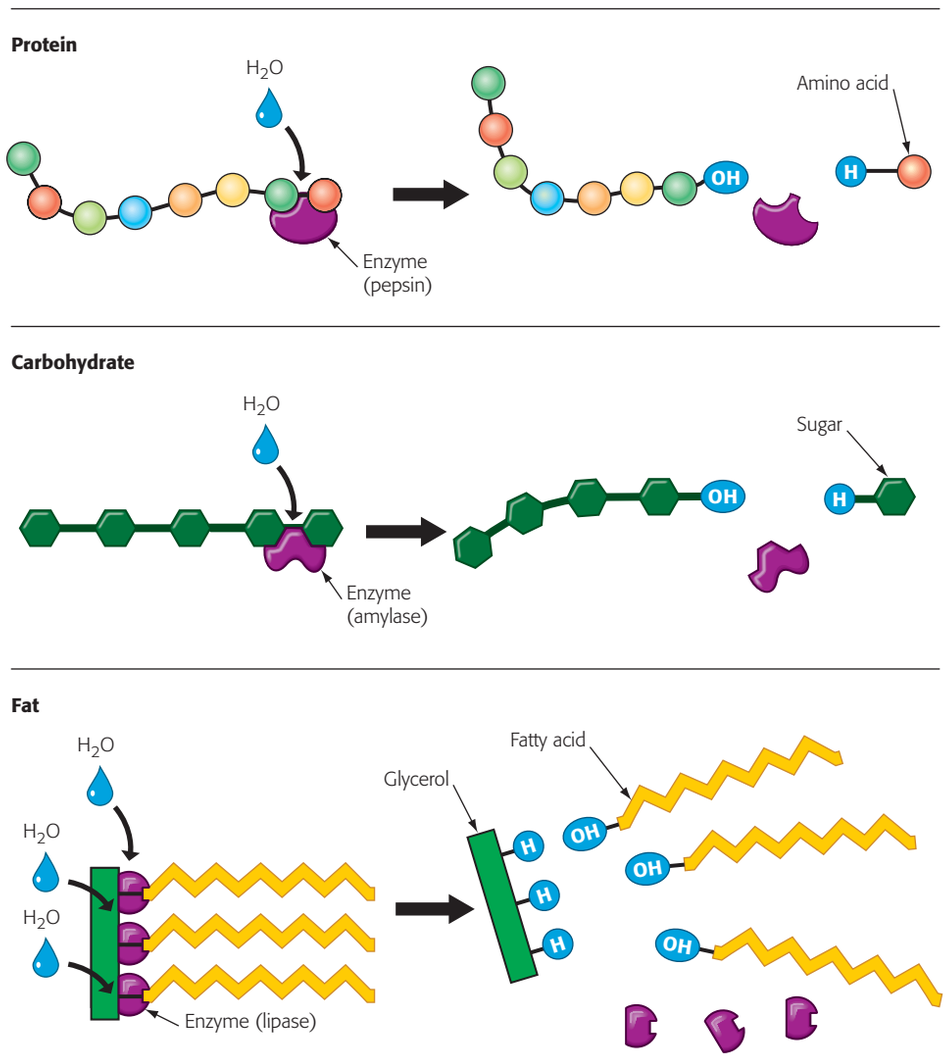
1. Place the four stages of food processing in their proper order: absorption, digestion, elimination, ingestion.
2. Food molecules are broken down into smaller molecules by enzymes that catalyze chemical reactions known as _____ reactions.

Answers: **1.** *ingestion, digestion, absorption, elimination* **2.** *hydrolysis*

▼ Figure 22.2 From cheese protein to human protein.



▼ Figure 22.3 Chemical digestion: hydrolysis of food molecules.
Digestive enzymes catalyze the breakdown of various types of food molecules by the addition of water molecules.



Digestive Compartments

How do animals digest their food without digesting their own cells and tissues? After all, digestive enzymes break down the same kinds of biological molecules that make up the animal body, and it is obviously important to avoid digesting yourself! A common solution to this problem has evolved in animals: Chemical digestion proceeds safely within some kind of compartment.

Digestion within a cell is the simplest type. In this process, a cell engulfs food by phagocytosis, forming a vacuole. This food vacuole then fuses with a lysosome containing enzymes, forming a digestive compartment (see Figure 4.16a). As food is digested, small food molecules pass through the vacuole membrane into the cytoplasm and nourish the cell. This type of digestion is common in protists, but sponges are the only animals that digest food solely within their cells.

✓ CHECKPOINT

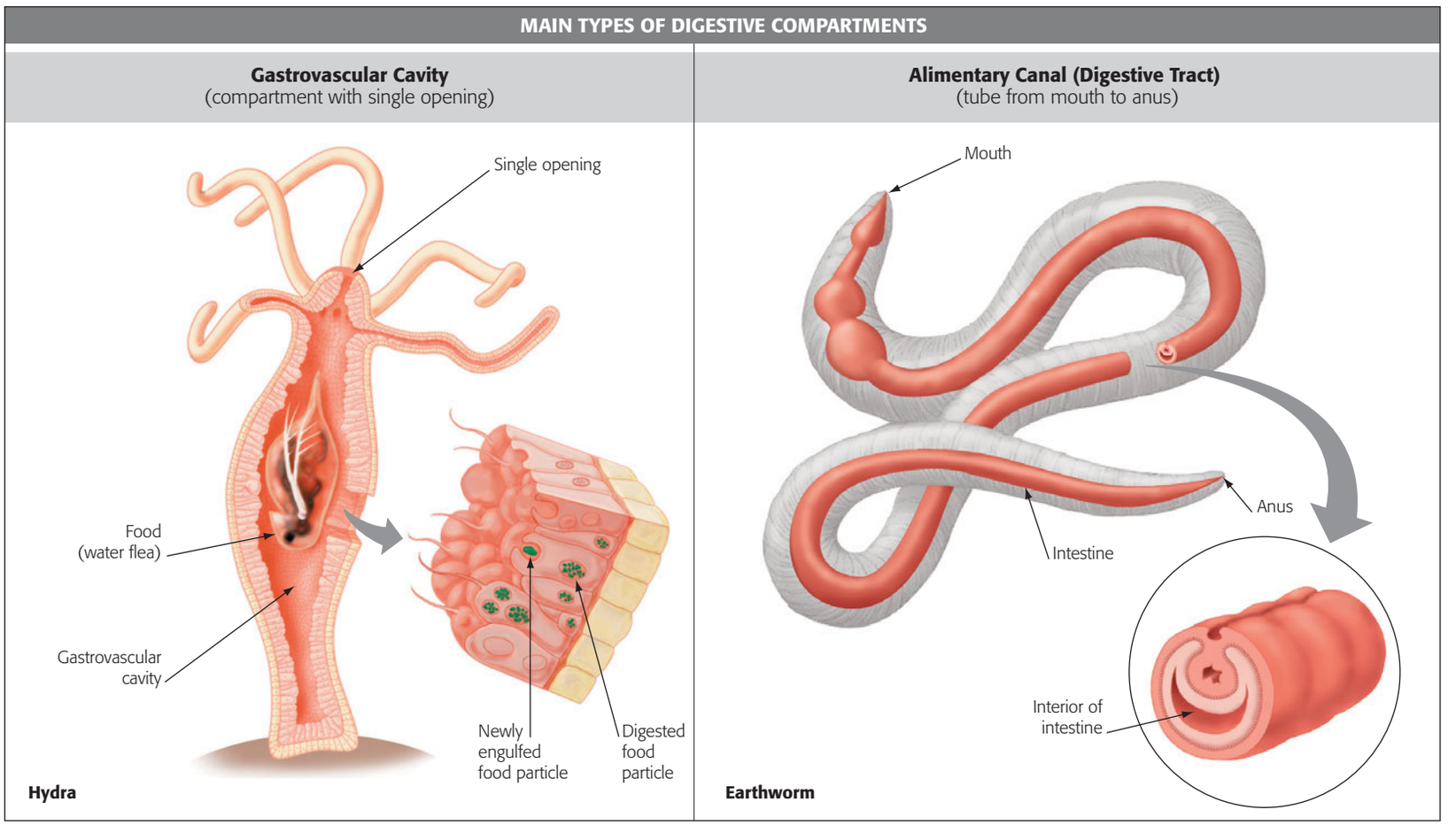
What is the main difference between gastrovascular cavities and alimentary canals?

Answer: Gastrovascular cavities have just one opening; alimentary canals have two (mouth and anus).

Most animals use a digestive compartment to process food (Figure 22.4). Such compartments allow animals to digest pieces of food that are much larger than a single cell. Simpler animals, including cnidarians (such as hydras and jellies) and flatworms, have a **gastrovascular cavity**, a digestive compartment with a single opening that functions as both the entrance for food and the exit for undigested wastes.

The vast majority of animals, including earthworms and humans, have a digestive tube with two separate openings, a mouth at one end and an anus at the other. Such a tube is called an **alimentary canal**, or **digestive tract**. Food moves through specialized regions that digest and absorb nutrients in a stepwise fashion. You know what an assembly line is; an alimentary canal is a *disassembly* line. Undigested wastes are eliminated from the alimentary canal as feces via the anus. ✓

▼ Figure 22.4 Main types of digestive compartments in animals.



A Tour of the Human Digestive System

We are now ready to follow our slice of pizza through the human alimentary canal, from mouth to anus. It's important to have a good map of the human digestive system so we don't get lost in there.

System Map

The human digestive system **(Figure 22.5)** consists of an alimentary canal (also called the gut) and several accessory organs (salivary glands, pancreas, liver, and gallbladder). The accessory organs secrete digestive chemicals into the alimentary canal via ducts (thin tubes). The human alimentary canal totals about 9 m (30 feet) in length. Such a long tube fits within a human body because it folds back and forth over itself with many switchbacks.

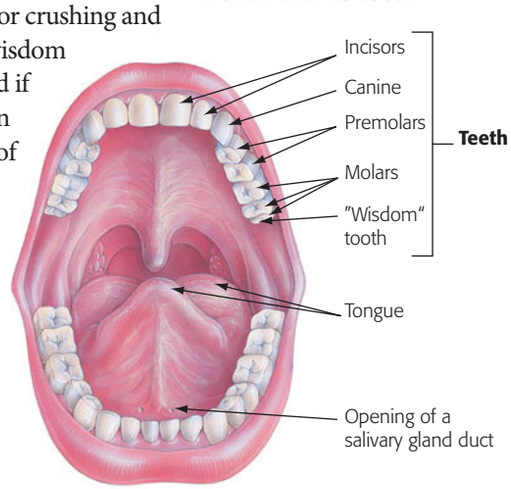
The alimentary canal is divided into specialized digestive organs along its length: mouth (oral cavity) → pharynx → esophagus → stomach → small intestine → large intestine (colon and rectum) → anus. You'll get a closer look at the structure and function of the digestive organs on our journey through the alimentary canal. As you reach each organ during our tour, look back at Figure 22.5 to find exactly where you are. First stop: the mouth.

The Mouth

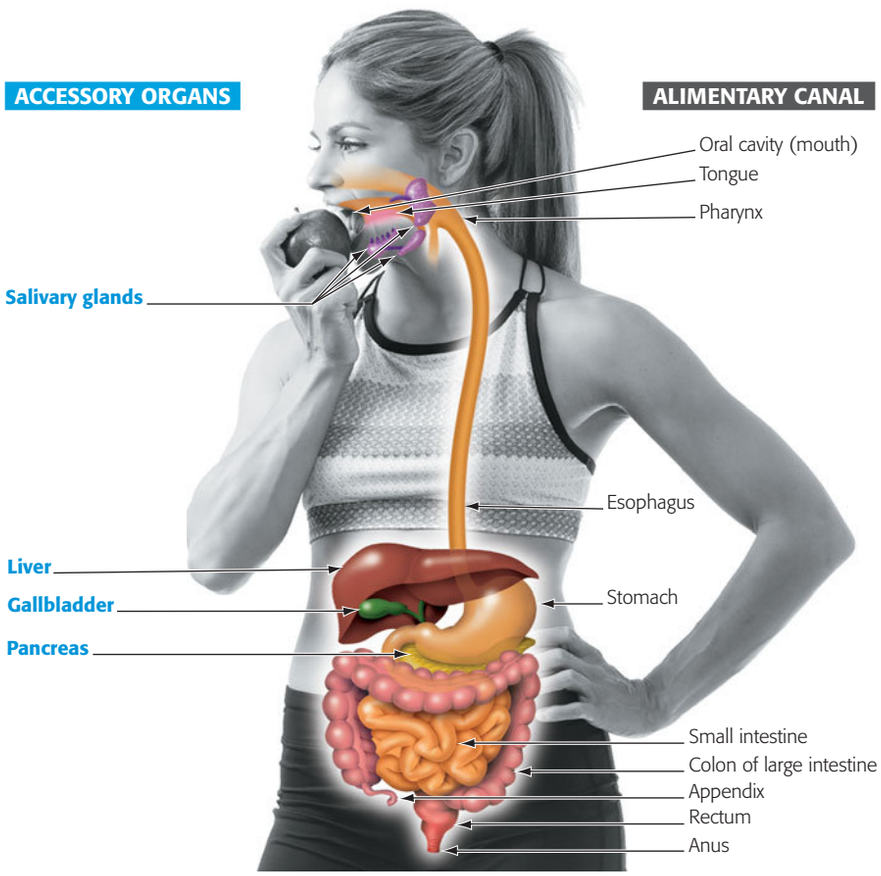
The **mouth** (also known as the **oral cavity**) is where we ingest (take in) food and begin to digest it **(Figure 22.6)**. Mechanical digestion begins here as our teeth cut, smash, and grind the food. Chewing makes food easier to swallow and exposes more surfaces of the food to digestive juices. Typically, an adult person has 32 teeth, which include bladelike incisors (that help bite off pieces of food), pointed canines (for ripping and tearing—think of the fangs of a dog or a wolf), and premolars and molars (for crushing and grinding). The last set of molars are called wisdom teeth; some people must have them removed if they push on other teeth. Chemical digestion also begins in the mouth with the secretion of saliva from **salivary glands**. Saliva contains the digestive enzyme salivary amylase. This enzyme breaks down starch, a major ingredient in pizza crust.

The muscular **tongue** is very busy during mealtime. Besides tasting the food, the tongue shapes it into a ball and pushes this food ball to the back of the mouth. Swallowing moves food into the pharynx. ☑

▼ **Figure 22.6 The human mouth and its teeth.**



► **Figure 22.5 The human digestive system.** The human digestive system consists of the alimentary canal (black labels) and accessory organs (blue labels).



☑ CHECKPOINT

In the oral cavity, chewing functions in _____ digestion, and salivary amylase initiates the chemical digestion of _____.

Answer: mechanical; starch (or polysaccharides)

The Pharynx

The chamber called the **pharynx**, located in your throat, is an intersection of the pathways for swallowing and breathing. The pharynx connects the mouth to the esophagus (part of the digestive system). But the pharynx also opens to the trachea, or windpipe, which leads to the lungs (part of the respiratory system). When you're not swallowing, the trachea entrance is open and you can breathe (**Figure 22.7**, left). Air enters the larynx (also called the voice box), flows past the vocal chords, through the trachea, and to your lungs. Men generally have larger larynxes and therefore more prominent Adam's apples (which are formed by cartilage on the outside of the larynx).

When you swallow, a reflex moves the opening of the trachea upward and tips a door-like flap called the epiglottis to close the trachea entrance (see Figure 22.7, right). Like a crossing guard at a dangerous intersection, the epiglottis directs the closing of the trachea, ensuring that the food will go down the esophagus. You can see this action in the bobbing of your Adam's apple every time you swallow. Occasionally, food begins to "go down the wrong pipe," which irritates the lining of the trachea and triggers a strong coughing reflex that helps keep your airway clear of food.

☑ CHECKPOINT

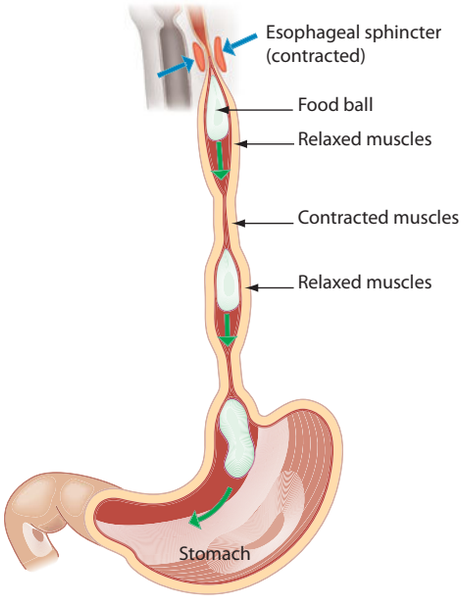
When we start coughing because food or drink "went down the wrong pipe," the material has entered the _____ instead of the _____.

Answer: trachea (windpipe); esophagus

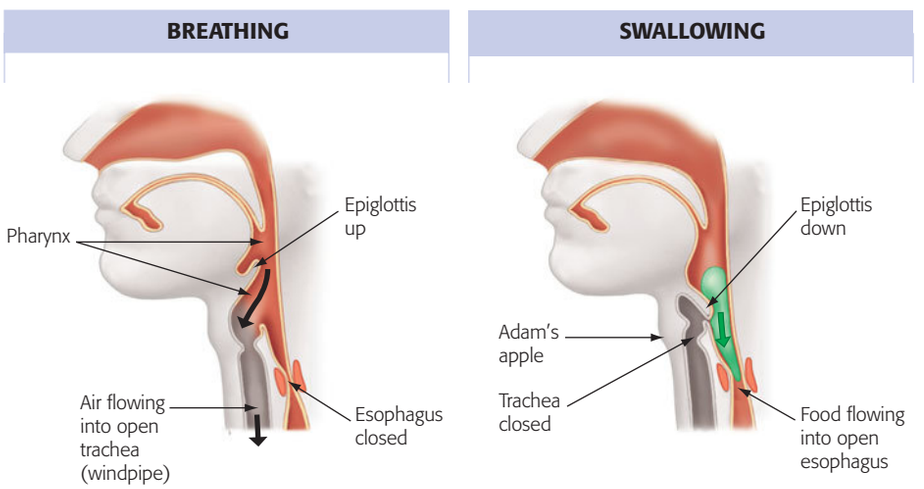
The Esophagus

The **esophagus** is a muscular tube that connects the pharynx to the stomach. Your esophagus moves food by **peristalsis**, alternating waves of muscular contraction and relaxation that squeeze the food ball along the esophagus **(Figure 22.8)**. It is this action that allows a lapping animal to swallow even when its head is lower than its stomach (like a cat at a water dish or a giraffe at a watering hole). Peristalsis propels food throughout the length of the alimentary canal. ☑

▼ Figure 22.8 The esophagus and peristalsis. Muscles of the esophageal wall contract just behind the food ball and relax just ahead of it.



▼ Figure 22.7 The epiglottis controls whether the pharynx is open to the lungs (left) or the stomach (right).



When you're not swallowing food or drink, air travels freely through the trachea (black arrows). The esophagus is closed.

When the food reaches the back of the mouth, a swallowing reflex is triggered. The top of the trachea rises against the epiglottis, closing the air passage, while the esophagus opens. Food travels down the esophagus (green arrow).

The Stomach

We do not have to eat constantly because the human **stomach** is a large organ that can store enough food to sustain us for several hours **(Figure 22.9)**. With its elastic wall and accordion-like folds, the stomach can stretch to hold about 2 liters (L)—more than half a gallon!—of food and drink.

The cells lining the stomach's interior secrete a digestive fluid called **gastric juice**. Gastric juice is made up of strong acid, digestive enzymes, and mucus. The acid in gastric juice is hydrochloric acid, and it is concentrated enough to dissolve iron nails. Gastric juice also contains **pepsin**, an enzyme that breaks proteins into smaller pieces.

When food passes from the esophagus into the stomach, the muscular stomach walls begin to churn, mixing the food and gastric juice into a thick soup called **chyme**. At the downstream end of the stomach, a sphincter (a ring of muscle) regulates the transfer of chyme from the stomach to the small intestine. With the chyme leaving the stomach only a squirt at a time, it takes about 2–6 hours for the stomach to empty after

a meal, long enough for stomach acids and pepsin to begin digestion. (Continued contraction of stomach muscles after the stomach is empty causes the "stomach growling" that lets everyone know you are hungry.)

With all of that acid, what keeps the stomach from digesting itself? Mucus coating the stomach lining helps protect it from gastric juices and from abrasive materials in the food. Timing is also a factor: Nerve and hormone signals regulate secretion of gastric juice so that it is discharged only when food is in the stomach. Even with these safeguards, gastric juice can still erode the stomach lining, requiring the production of new cells by cell division. In fact, your stomach replaces its lining completely about once every three days.

Stomach Ailments

Gastric juice can be harmful. Occasional backflow of chyme causes pain in the esophagus, commonly but inaccurately called "heartburn" (it should really be called "esophageal burn"). Some people suffer this backflow frequently and severely enough to harm the lining of the esophagus, a condition known as acid reflux or GERD (gastroesophageal reflux disease).

If the stomach lining is eroded by gastric juice faster than it can regenerate, painful open sores called gastric ulcers can form in the stomach wall. The cause of most ulcers is not stress, as was once thought, but infection of the stomach lining by an acid-tolerant bacterium called *Helicobacter pylori*. The metabolism of these bacteria damages the coat of mucus, making the lining more accessible to gastric juice. In severe ulcers, the erosion can produce a hole in the stomach wall and cause life-threatening internal bleeding and infection. (The cause of ulcers was established in 1984 when biologist Barry Marshall experimented on himself by drinking beef soup laced with *H. pylori* bacteria; although Marshall eventually won a 2005 Nobel Prize for his work, we do not recommend this kind of experimentation!) Most stomach ulcers are treated with antibiotics. Affected people can also get relief by taking medications that contain bismuth, which helps reduce ulcer symptoms and may kill some bacteria.

Weight Loss Surgeries

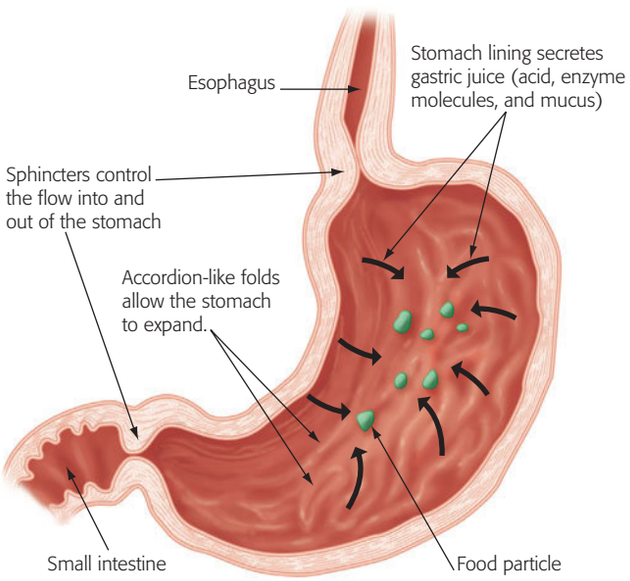
Some people who are severely obese can shed pounds by diet and exercise. But others who cannot are candidates for weight loss surgery. The most common weight loss surgery in the United States (with about 150,000 operations each year) is gastric bypass. Staples are used to reduce the stomach to about the size of a chicken egg, and the first 18 inches of the small intestine are bypassed by attaching the downstream intestine directly to the reduced stomach pouch **(Figure 22.10)**. As a result, patients quickly feel full, and the body's ability to absorb food is reduced. When accompanied by a healthy lifestyle, weight loss surgeries are successful in 90% of patients. However, all surgeries carry risks (there is about a 1% mortality rate), and patients must carefully monitor their diet to ensure proper nutrition. Weight loss surgeries can be effective, but many health professionals recommend them only as a last resort. ☑

☑ CHECKPOINT

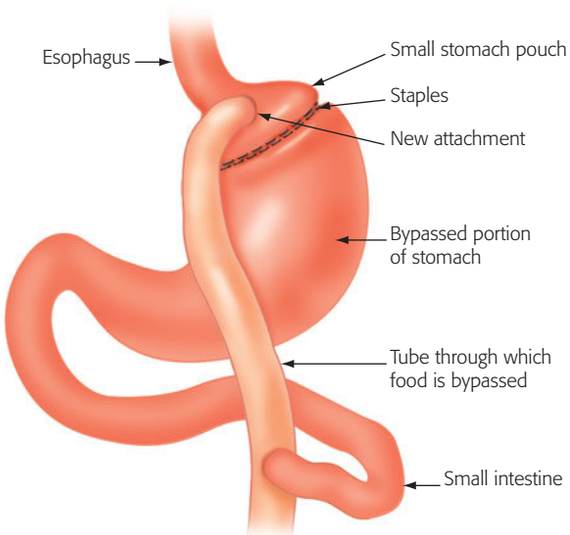
Why are antibiotics an effective treatment for most gastric ulcers?

Answer: The antibiotics kill bacteria that damage the stomach lining.

▼Figure 22.9 The human stomach.



▼Figure 22.10 Gastric bypass surgery. An incision is made in the small intestine about 18 inches from where it joins the stomach. The free end of the intestine is then attached to the smaller stomach pouch, which now has a significantly reduced capacity to store food.



The Small Intestine

The **small intestine**, at a length of about 6 m (about 20 feet), is the longest part of the alimentary canal. Although this intestine isn't small in length, it is small in diameter—only 2.5 cm (about the width of a quarter) across, compared with the large intestine, which is 5 cm across. The small intestine is the major organ for chemical digestion and for absorption of nutrients into the bloodstream.

Chemical Digestion in the Small Intestine

What shape is our pizza in by the time it reaches the small intestine? At that point, mechanical digestion has turned the pizza into a thick, nutrient-rich soup. Chemical digestion by salivary amylase and gastric pepsin has initiated breakdown of the pizza's starch and proteins. Now the small intestine takes over with an arsenal of enzymes that dismantle the food molecules into smaller molecules. These enzymes are mixed with chyme in the first 25 cm or so (about a foot) of the small intestine, the region called the **duodenum**.

The duodenum receives digestive juices from the pancreas, liver, gallbladder, and the intestinal lining itself (**Figure 22.11**). The **pancreas** is a large gland that secretes pancreatic juice into the duodenum via a duct. Pancreatic juice neutralizes the stomach acid that enters the duodenum, and it contains enzymes that aid in digestion. As peristalsis propels the mix along the small intestine, these enzymes contribute to the continuing breakdown of food molecules.

Bile is a juice produced by the **liver**, stored in the **gallbladder**, and secreted through a duct into the duodenum. Bile contains salts that break up fats into small droplets that are more susceptible to dismantling by digestive enzymes. Bile sometimes crystallizes to form gallstones, which can cause pain by obstructing the gallbladder or its ducts. Often the only cure is surgical removal of the gallbladder, which usually has no long-lasting effect on digestion because the liver still produces and secretes bile.

What are gallstones and what causes them?

Absorption of Nutrients

In the small intestine, the broken-down food molecules are ready for absorption into the body. Wait a minute! Aren't these nutrients already in the body? Not really. The alimentary canal is a tube running through the body, and its cavity is continuous with the great outdoors. The doughnut analogy shown in **Figure 22.12** should convince you that this is so. Until nutrients actually cross the tissue lining the alimentary canal to enter the bloodstream, they are still *outside* the body. If it were not for nutrient absorption, we could eat and digest huge meals but still starve.

Figure 22.11 The duodenum. Chyme squirted from the stomach into the duodenum is mixed with digestive juices from the pancreas, liver, gallbladder, and the lining of the duodenum itself.

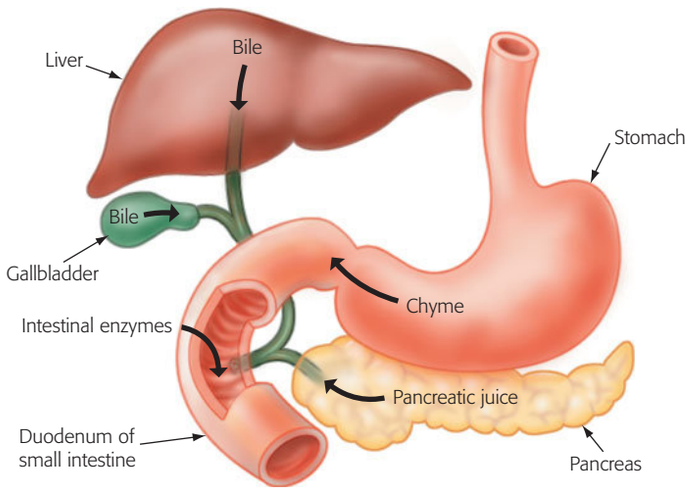
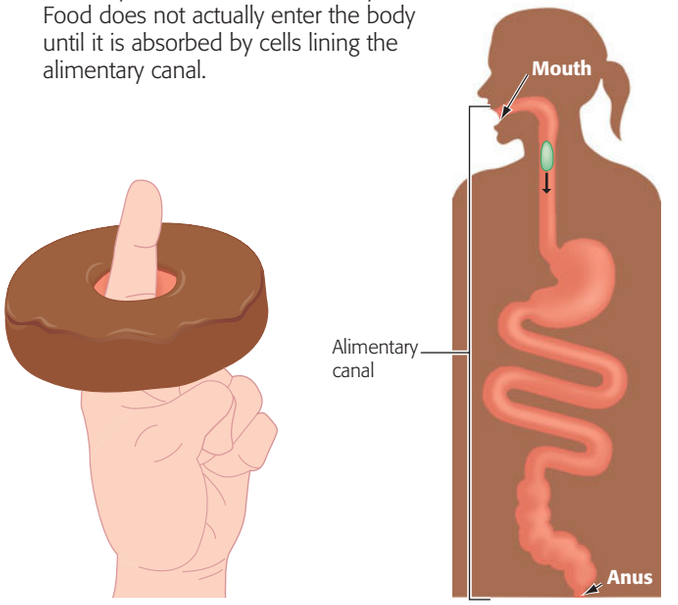


Figure 22.12 Nutrients within the small intestine are not yet inside the body. Imagine an elongated doughnut that's analogous to the "tube-within-a-tube" anatomy of the human alimentary canal. Food does not actually enter the body until it is absorbed by cells lining the alimentary canal.

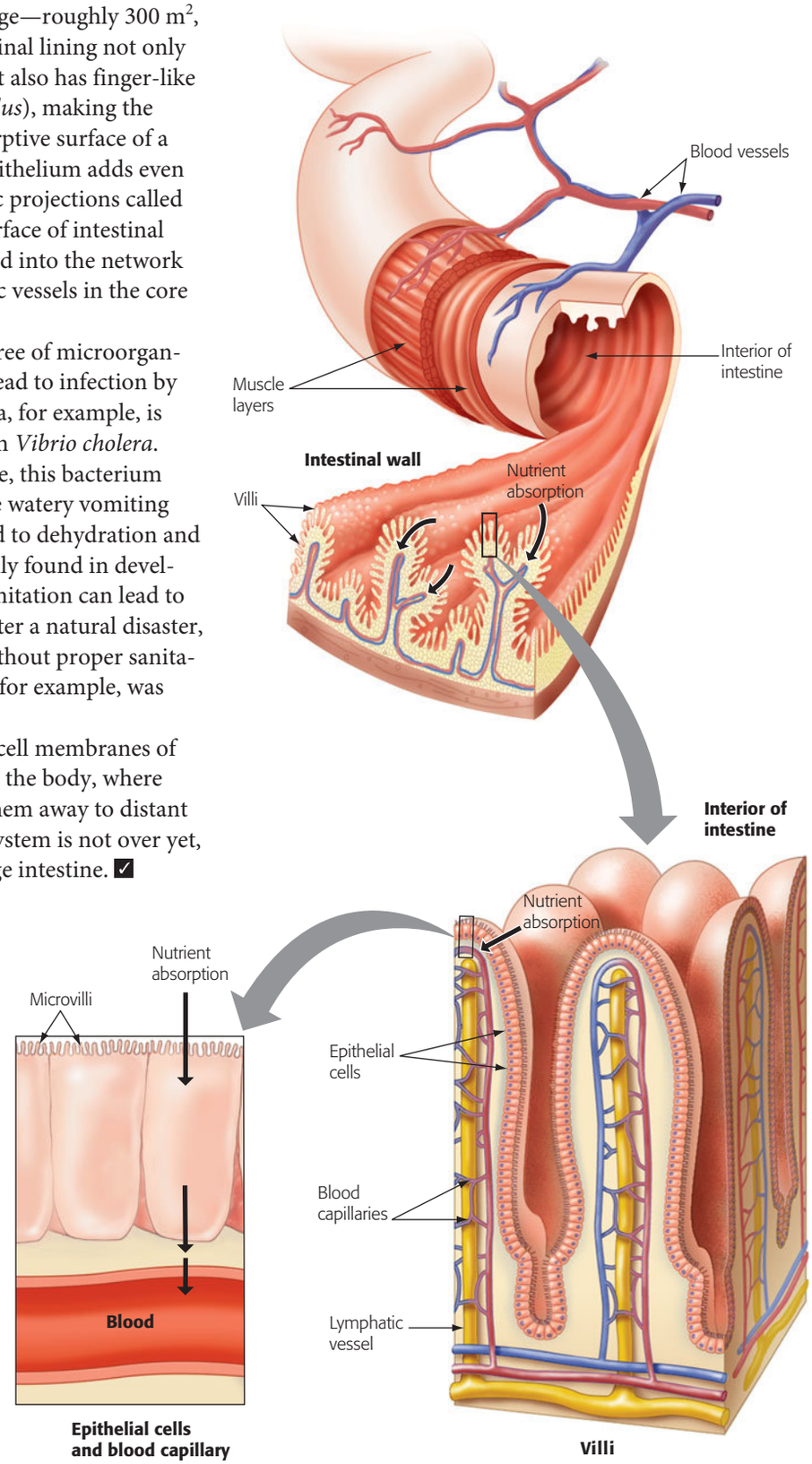


A finger through a hole **Food through the alimentary canal**

Most digestion is complete by the time what's left of the pizza reaches the end of the duodenum. The next several meters of the small intestine are specialized for nutrient absorption. The structure of the intestinal lining, or epithelium, fits this function **(Figure 22.13)**. The surface area of this epithelium is huge—roughly 300 m^2, the size of a tennis court. The intestinal lining not only has large folds, like the stomach, but also has finger-like outgrowths called villi (singular, *villus*), making the epithelium something like the absorptive surface of a fluffy bath towel. Each cell of the epithelium adds even more surface by having microscopic projections called microvilli. Across this expansive surface of intestinal epithelium, nutrients are transported into the network of small blood vessels and lymphatic vessels in the core of each villus.

Normally, the small intestine is free of microorganisms. But improper sanitation can lead to infection by various bacteria. The disease cholera, for example, is caused by ingestion of the bacterium *Vibrio cholera*. As it multiplies in the small intestine, this bacterium releases a toxin that leads to profuse watery vomiting and diarrhea, which in turn can lead to dehydration and eventually death. Cholera is primarily found in developing nations, where inadequate sanitation can lead to outbreaks. Cholera often appears after a natural disaster, when many people are displaced without proper sanitation. The 2010 earthquake in Haiti, for example, was followed by a cholera epidemic.

After nutrients have crossed the cell membranes of the microvilli, they are finally *inside* the body, where the bloodstream and lymph carry them away to distant cells. But our tour of the digestive system is not over yet, because we still have to visit the large intestine. ☑



► **Figure 22.13 The small intestine and nutrient absorption.** Folds with projections (villi) that have even smaller projections (microvilli) give the small intestine an enormous surface area for nutrient absorption (black arrows). Most nutrients are transported across the microvilli into blood capillaries.

☑ CHECKPOINT

The major sites for absorption of nutrients in the human body are the _____ of the _____.

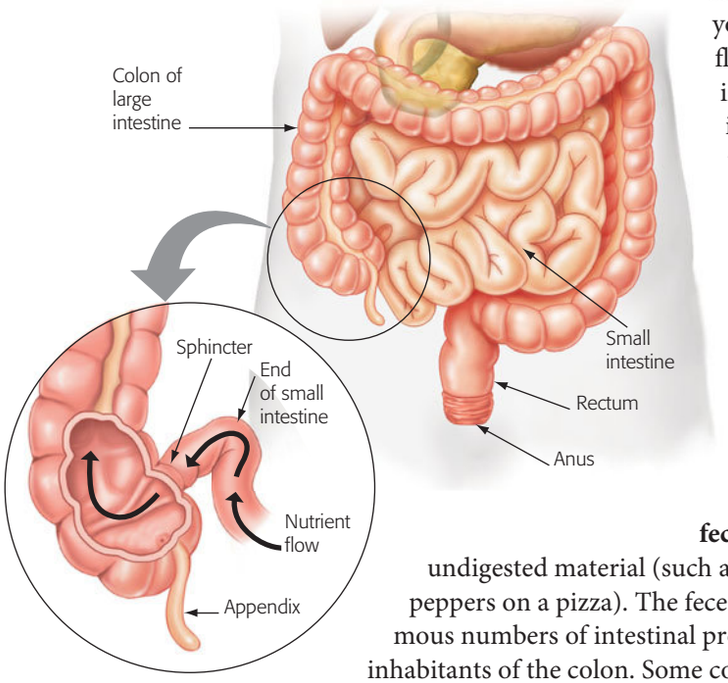
Answer: *microvilli; small intestine*

The Large Intestine

At only 1.5 m (5 feet) in length, the **large intestine**, the main portion of which is called the **colon**, is shorter than the small intestine but is called "large" because it is almost twice as wide (about 5 cm). Where the two organs join, a sphincter controls the passage of what's left of a meal **(Figure 22.14)**. Nearby is a small finger-like extension called the **appendix**. The appendix contains white blood cells that make minor contributions to the immune system. If the junction between the appendix and the colon becomes blocked, appendicitis—a bacterial infection of the appendix—may result. Emergency surgery is usually required to remove the appendix and prevent the spread of infection.

Why is a burst appendix a medical emergency?

▼Figure 22.14 The large intestine and its connection to the small intestine.



The main function of the colon is to absorb water from the alimentary canal. About 7 L (not quite 2 gallons) of digestive juice per day spill into your digestive tract. About 90% of the water it contains is absorbed back into your blood and tissue fluids, with the small intestine reclaiming much of the water and the colon finishing the job. As water is absorbed, undigested materials from the meal become more solid as they are conveyed along the colon by peristalsis. The end product is **feces**, consisting of undigested material (such as cellulose from peppers on a pizza). The feces also contain enormous numbers of intestinal prokaryotes, normal inhabitants of the colon. Some colon bacteria, such as *Escherichia coli*, produce B vitamins and vitamin K that are absorbed through your colon wall and help supplement your diet.

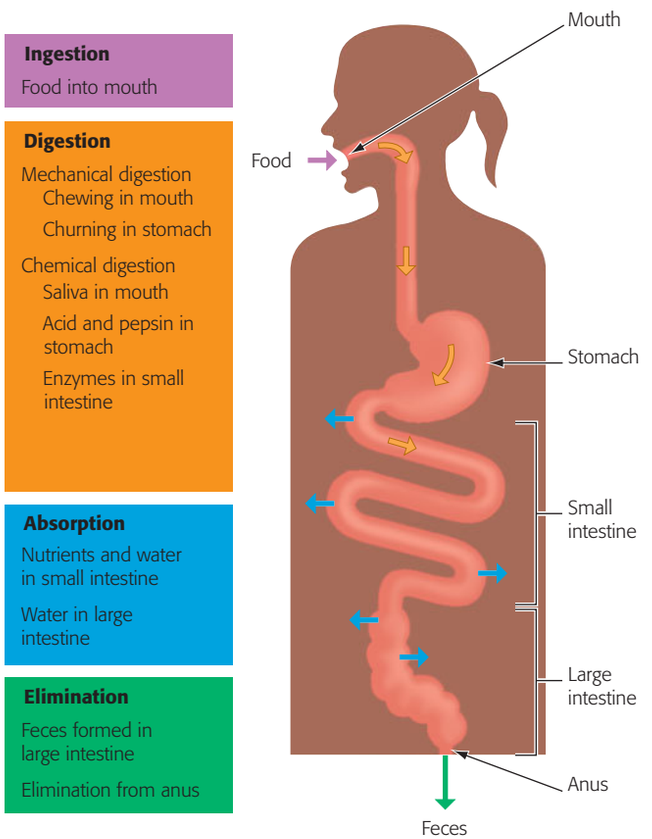
If the lining of the colon is irritated by a viral or bacterial infection (sometimes mistakenly called "stomach bugs"), diarrhea may result because the colon cannot reabsorb water efficiently. Prolonged diarrhea can cause life-threatening dehydration, particularly among the very young and very old. The opposite problem, constipation, occurs when peristalsis moves feces along too slowly and the colon reabsorbs so much water that the feces become too compacted. Constipation can result from lack of exercise or from a diet that does not include enough plant fiber.

Several intestinal disorders are characterized by inflammation (painful swelling) of the intestinal wall. Celiac disease results when gluten, a protein found in wheat, triggers an immune reaction that leads to swelling and a lack of nutrient absorption. The only treatment is a lifelong gluten-free diet. An inappropriate immune response also causes Crohn's disease, a chronic inflammation that can periodically flare up along any part of the alimentary canal. Investigating the cause and treatment of Crohn's disease is an active area of medical research.

The **rectum**, the last 15 cm (6 inches) of the large intestine, stores feces until they can be eliminated. Contractions of the colon and the rectum create the urge to defecate. Two rectal sphincters, one voluntary and the other involuntary, regulate the opening of the **anus**. When the voluntary sphincter is relaxed, contractions of the rectum expel feces.

From entrance to exit, we have now followed a pizza slice all the way through the alimentary canal. **Figure 22.15** stretches out the tube to help you review food processing along its length. ☑

▼Figure 22.15 Review of food processing in the human alimentary canal.



☑ CHECKPOINT

What is the main function of the large intestine?

Answer: water reabsorption

Human Nutritional Requirements

For any animal, proper nutrition provides fuel for cellular work, materials for building molecules, and essential nutrients for health. A healthy human diet is rich in whole grains, vegetables, fruits, and calcium, along with moderate quantities of protein from lean meat, eggs, nuts, or beans. Nutritionists recommend limited consumption of fats and sugars (primarily to help maintain a healthy weight) as well as salt.

Food as Fuel

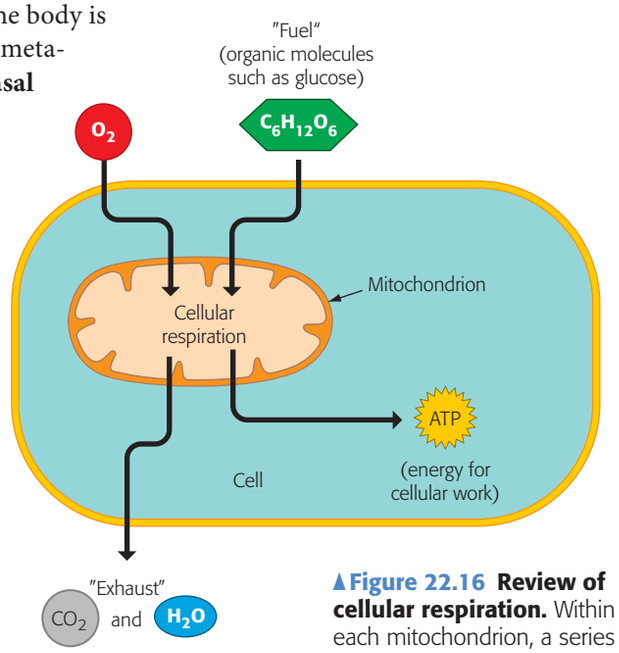
Cells can extract energy stored in the organic molecules of food through the process of cellular respiration (described in detail in Chapter 6) and expend that energy as cellular work. Using oxygen, cellular respiration breaks down sugar and other food molecules. This process generates many molecules of ATP for cells to use as a direct source of energy and releases carbon dioxide and water as waste "exhaust" **(Figure 22.16)**.

Calories

Calories are a measure of the energy stored in your food as well as the energy you expend during daily activities. One **calorie** is the amount of energy required to raise the temperature of a gram of water by 1°C. But such a tiny amount of energy is not very useful from a human perspective. We can scale up with the **kilocalorie** (1 **kcal** = 1,000 calories). Now, for a wrinkle in these definitions: The "Calories" (with an uppercase C) listed on food labels are actually kilocalories. So the 280 or so Calories in a slice of thick-crust pepperoni pizza are actually 280 kcal. That's a whole lot of fuel for making ATP. However, about 60% of our food energy is lost as heat that dissipates to the environment. You know this effect from being in a crowded room; each person produces as much heat as a 75-watt light bulb.

Metabolic Rate

How fast do we "burn" our food? The rate of energy consumption by the body is called **metabolic rate**. Your metabolic rate is equal to your **basal metabolic rate (BMR)**, the amount of energy it takes just to maintain your basic body functions, plus any additional energy consumption above that base rate. BMRs for people average about 1,300–1,500 kcal per day for adult females and 1,600–1,800 kcal per day for adult males. The more active you are, the greater your actual metabolic rate and the greater the number of calories your body uses per day. Metabolic rate also depends on other factors, such as body size, age, stress level, and heredity.



▲ **Figure 22.16 Review of cellular respiration.** Within each mitochondrion, a series of chemical reactions extracts energy from fuel molecules and generates ATP, a chemical that provides energy for most cellular work.

The examples in **Table 22.1** give you an idea of the amount of activity that it takes to use up the kilocalories in several common foods. As discussed in the Biology and Society section, balancing the calories you take in (via your diet) and the calories you expend (via exercise) can help you manage your weight. Caloric balance, however, does not ensure good nutrition, and food is our source of substance as well as our source of energy. ☑

Table 22.1 Exercise Required to Burn the Calories (kcal) in Common Foods

	Jogging (9 min/mi)	Playing Soccer	Walking (2 min/mi)
kcal "burned" per hour*	775	477	245
Ice cream (1 cup, premium style), 500 kcal	39 min	1 hr, 3 min	2 hr, 2 min
Cheeseburger (quarter-pound), 417 kcal	32 min	52 min	1 hr, 42 min
Pepperoni pizza (1 large slice), 280 kcal	22 min	35 min	1 hr, 8 min
Soft drink (12 oz), 152 kcal	12 min	19 min	37 min
Apple (medium), 100 kcal	8 min	13 min	24 min
Whole wheat bread (1 slice), 65 kcal	5 min	8 min	16 min

**These data are estimated for a person weighing 68 kg (150 pounds).*

☑ CHECKPOINT

1. What cellular process ultimately uses the energy stored in food molecules?
2. If you eat 1,000 Calories in a day, would you be likely to gain weight?

Answers: **1.** cellular respiration **2.** No. Chances are your basal metabolic rate is higher than that, so you would lose a bit of weight.

Food as Building Material

Even if you have stopped growing, your health depends on the continuous repair and maintenance of your tissues. The building materials required for such work are provided by the small organic molecules (monomers) produced during the digestion of food. Your cells can reassemble those smaller molecules into various large biological molecules (polymers), such as your own unique proteins and DNA.

Within limits, your metabolism can change organic material from one form to another and compensate for nutrients that are lacking in your diet. For instance, if a cell has a shortage of a particular amino acid, it may be able to make that amino acid from an excess supply of another amino acid. However, certain substances—the **essential nutrients**—cannot be made from any other materials, so the body needs to receive them in preassembled form. A healthful diet must include adequate amounts of all of the essential nutrients: essential amino acids, vitamins, minerals, and essential fatty acids. ☑

☑ CHECKPOINT

What is an essential nutrient?

Answer: a substance that an animal requires in the diet but cannot make

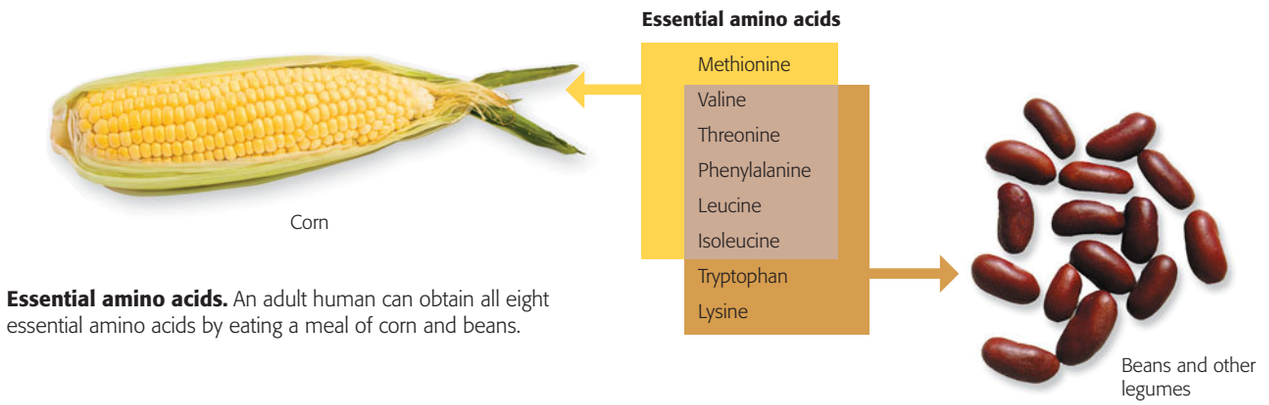
Essential Amino Acids

All proteins are built from 20 different kinds of amino acids (see Figure 3.16). Twelve of the 20 amino acids can be manufactured by the adult body from other compounds. The other eight are **essential amino acids**: They must be obtained from the diet because human cells cannot make them. (Infants also require a ninth, histidine.)

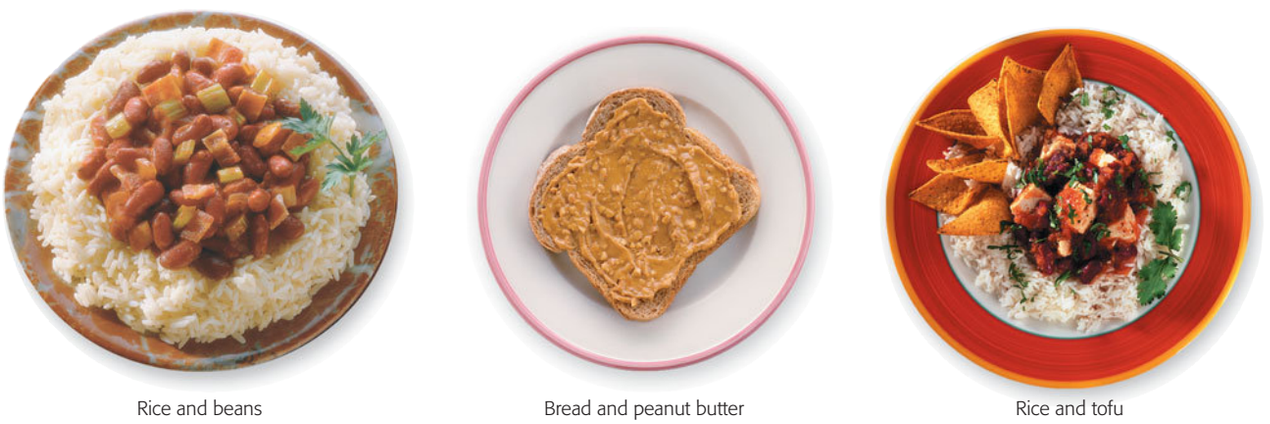
Different foods contain different proportions of amino acids. Animal proteins, such as those in meat, eggs, and milk, are said to be "complete" because they provide adequate amounts of all the essential amino acids. In contrast, most plant proteins are incomplete, meaning they are deficient in one or more of the essential amino acids. If you are a vegetarian (by choice or, as for much of the world's population, by economic necessity), the key to good nutrition is to eat a variety of plants that together provide all of the essential amino acids.. The combination of a grain and a legume (such as beans, peanuts, or peas) often provides the right balance **(Figure 22.17)**. Most societies have a staple meal that includes such a combination.

What makes red beans and rice so healthy?

▼ Figure 22.17 Essential amino acids from a vegetarian diet.



Essential amino acids. An adult human can obtain all eight essential amino acids by eating a meal of corn and beans.



Complete meals. Many societies have a staple meal that provides a complete set of essential amino acids by combining a grain with a legume.

Vitamins

Organic molecules that are required in the diet in very small amounts are called **vitamins**. For example, one tablespoon of vitamin B_{12} can provide the daily requirement of nearly a million people. There are 13 vitamins essential to human health **(Table 22.2)**. Most are needed because they assist enzymes. Deficiencies in any essential vitamin can cause serious health problems.

People who eat a balanced diet should be able to obtain enough of all needed nutrients in their food. For others, vitamin supplements can fill in the gaps, but supplements should not be used indiscriminately because overdoses of some vitamins (such as A, D, and K) can be harmful. ☑

Table 22.2 Vitamins

Vitamin	Major Dietary Sources	Interesting Facts
Water-Soluble Vitamins		
Vitamin B_1 (thiamine)	Pork, legumes, peanuts, whole grains	Too little thiamin leads to the disease beriberi; refined grains (like polished white rice) lack thiamin.
Vitamin B_2 (riboflavin)	Dairy products, organ meats, enriched grains, vegetables	Deficiency causes photophobia (aversion to light).
Niacin	Nuts, meats, fish, grains	High doses reduce cholesterol but can cause hot flashes. Too little leads to the disease pellagra, which can be deadly.
Vitamin B_6 (pyridoxine)	Common in most foods: meats, vegetables, whole grains, milk, legumes	Deficiency is rare.
Pantothenic acid	Most foods: meats, fish, dairy, whole grains	Deficiency is rare but can lead to fatigue.
Folic acid (folate)	Green leafy vegetables, oranges, nuts, legumes, whole grains, fortified foods	Recommended for women of childbearing age because it cuts in half the risk of some birth defects involving development of the spinal cord.
Vitamin B_{12}	Animal products: meats, eggs, dairy	It's hard for vegans to get enough B_{12} in their diet, and some intestinal disorders (such as Crohn's disease or celiac disease) may cause deficiencies.
Biotin	Legumes, most vegetables, meats, milk, liver, egg yolks	For most people, adequate levels are provided by intestinal bacteria.
Vitamin C (ascorbic acid)	Raw fruits and vegetables, especially citrus fruits, broccoli, cabbage, tomatoes, green peppers, strawberries	Many animals can produce their own vitamin C, but humans cannot. Deficiency causes the disease scurvy, which was a significant health problem during the era of lengthy sea voyages.
Fat-Soluble Vitamins		
Vitamin A	Dark green and orange vegetables and fruits, dairy products	Too little in the diet can lead to vision loss. Too much can cause yellow/orange skin.
Vitamin D	Fortified dairy products, egg yolk; also made in human skin in presence of sunlight	Aids calcium absorption. Too little causes rickets (bone deformities).
Vitamin E (tocopherol)	Green leafy vegetables, oils, nuts, seeds, wheat germ	Deficiency is rare.
Vitamin K	Green vegetables, vegetable oils	Needed for blood clotting. Produced by intestinal bacteria, so newborns and people taking long-term antibiotics may be deficient.



☑ CHECKPOINT

Why do vegetarians have to be particularly careful to get proper amounts of the essential amino acids?

Answer: because few plant products contain all of them

Minerals

The organic molecules in our diet, such as carbohydrates, fats, and proteins, provide the four chemical elements most abundant in our body: carbon, oxygen, hydrogen, and nitrogen. We also require smaller amounts of 21 other chemical elements (see Figure 2.2) that are acquired mainly in the form of inorganic nutrients called **minerals**. Like vitamin deficiencies, mineral deficiencies can cause health problems. For example, calcium is needed as a building material for your bones and teeth and for the proper functioning of nerves and muscles. It can be obtained from dairy products, legumes, and dark green vegetables such as spinach. Too little calcium can result in the degenerative bone disease osteoporosis.

Mineral excesses can also cause problems. For example, we require sodium for our nerves and muscles to function, but the average American consumes about 20 times the required amount of sodium, mainly in the form of salt (sodium chloride) added to processed foods. Excess sodium can contribute to high blood pressure.

Essential Fatty Acids

Our cells make fats and other lipids by combining fatty acids with other molecules, such as glycerol (see Figure 3.11). We can make most of the required fatty acids, in turn, from simpler molecules; those we cannot make, called **essential fatty acids**, we must obtain in our diet. One essential fatty acid, linoleic acid (one of the omega-6 family of fatty acids), is especially important because it is needed to make some of the phospholipids of cell membranes. Most diets furnish ample amounts of the essential fatty acids, so deficiencies are rare.

Which fats are good for you?

Decoding Food Labels

To help consumers assess the nutritional value of packaged foods, the U.S. Food and Drug Administration (FDA) requires two blocks of information on labels **(Figure 22.18)**. One lists the ingredients (by weight) from greatest amount to least. The other lists key nutrients, emphasizing the ones associated with disease and the ones associated with a healthy diet. You should note the serving size and adjust the rest of the nutritional information to reflect your actual serving. For example, if the serving size is 1 cup of cereal but you're eating 2 cups, double all of the other values. You'll see a wide variety of data—including Calories, fat, cholesterol, carbohydrates, fiber, protein, vitamins, and minerals—expressed as amounts per serving and as percentages of a daily value. (Daily values are based on a 2,000-Calorie-per-day diet; these values are therefore "one-size-fits-all" numbers that should be used only as rough guidelines.) If you pay attention, you'll find that serving sizes are often surprising; a single cookie or a snack-sized bag of chips may actually contain multiple servings and therefore many more calories than a quick glance would indicate. Reading food labels carefully can help you make informed choices about what you put into your body. ☑



► **Figure 22.18** **FDA-required food labels.**

☑ CHECKPOINT

1. What is the difference between vitamins and minerals?
2. How many slices of the bread in Figure 22.18 would an average person have to eat to obtain the daily value of fiber?

*Answers: **1.** Both are required in the diet for proper health, but vitamins are organic compounds, whereas minerals are elements. **2.** nine slices*

Nutritional Disorders

Considering the central role that nutrients play in a healthy body, it is not surprising that dietary problems can have severe health consequences. In this section, we examine some common nutritional disorders.

Malnutrition

Living in an industrialized country where food is plentiful and most people can afford a decent diet, we may find it hard to relate to starvation. But 800 million people around the world—nearly three times the population of the United States—must cope with hunger. As difficult as it is to imagine, 14,000 children under the age of 5 starve to death *each day*.

The main type of nutritional deficiency is **malnutrition**, health problems caused by an improper or insufficient diet. Malnutrition may be caused by inadequate intake or medical problems (such as metabolic or digestive abnormalities). On a global scale, protein deficiency—insufficient intake of one or more essential amino acids—causes the most suffering, mainly in less industrialized countries.

Protein deficiency is most common where there is a great gap between food supply and population size. The most reliable sources of essential amino acids are animal products, but these foods are expensive. People forced by economic necessity to get almost all their calories from a single plant staple, such as corn or potatoes, will suffer deficiencies of essential amino acids.

Most victims of protein deficiency are children, who are likely to develop poorly both physically and mentally—if they even survive infancy. The resulting syndrome is called kwashiorkor, from the Ghanaian word for "rejected one," a reference to the onset of the disease when a child is weaned from its mother's milk and placed on a starchy diet after a sibling is born (Figure 22.19). The problem of protein deficiency in some less industrialized countries has been compounded by a trend away from breast-feeding altogether.

Eating Disorders

Millions of Americans, mostly female, are affected by malnutrition because of an eating disorder. **Anorexia nervosa** is characterized by self-starvation due to an intense fear of gaining weight, even when the person is underweight. **Bulimia** is a behavioral pattern of binge eating followed by purging through induced vomiting, abuse of laxatives, or excessive exercise. Both disorders are characterized by an obsession with body weight and shape and can result in serious health problems.

The causes of anorexia and bulimia are unknown, but certain people may be more prone to develop eating disorders than others because of differences in genetics, psychology, and brain chemistry. Culture also seems to be a factor: Anorexia and bulimia occur almost exclusively in affluent industrialized countries, where food is plentiful but thinness is idealized. Treatment options include counseling and antidepressant medications. Some people suffering from anorexia and bulimia eventually develop healthy eating habits without treatment. But for many, dysfunctional nutrition becomes a long-term problem that can impair health and even lead to death. ☑

☑ CHECKPOINT

What is the difference between anorexia and bulimia?

Answer: *Anorexia is self-starvation; bulimia is a pattern of binge eating and purging.*

▼Figure 22.19 Kwashiorkor in a Sudanese boy. Kwashiorkor, a form of malnutrition caused by inadequate protein in the diet, causes fluid to enter the abdominal cavity, producing swelling of the belly.



Obesity

In the United States and many other industrialized countries, overnourishment is the nutritional disorder of greatest concern. **Obesity** is defined as a too-high **body mass index (BMI)**, a ratio of weight to height. About one-third of all Americans are obese, and another one-third are overweight (a BMI that is between normal and obese). Obesity increases the risk of heart attack, diabetes, and several other diseases.

What does your BMI say about you?

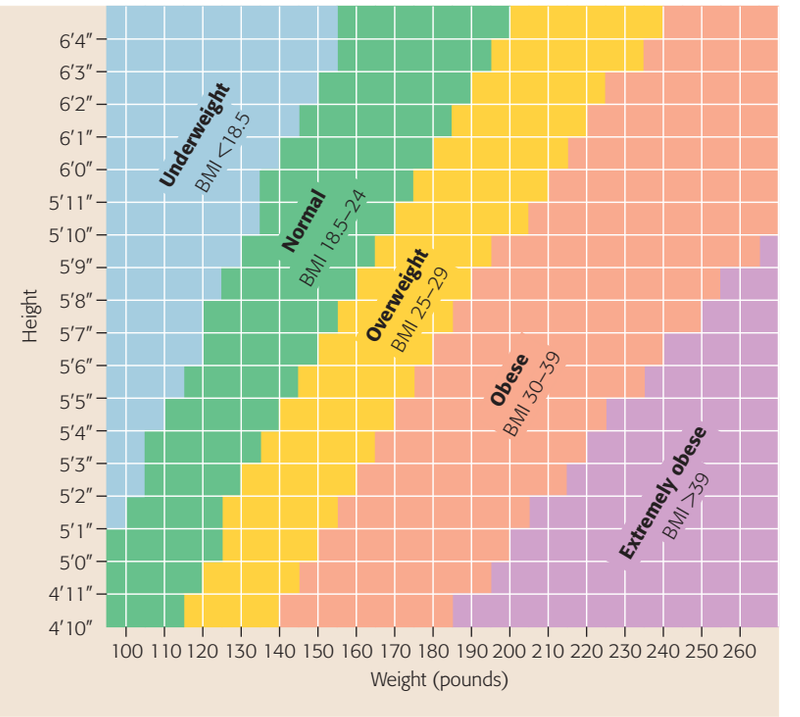
It is important to realize that not being as slim or well toned as a magazine model does not mean that you are obese. Researchers continue to debate how heavy we can be before we are considered unhealthy. And keep in mind that BMI is only an approximation that does not, for example, take into account body mass from muscle versus body mass from fat. Reflecting this uncertainty, BMI charts show a range of acceptable values (Figure 22.20). Further complicating matters, a tendency toward obesity is inherited to some extent, as we'll see next. ☑

☑ CHECKPOINT

What BMI category is a person who is 6 feet 4 inches tall and weighs 230 pounds?

Answer: overweight

▼Figure 22.20 Body mass index (BMI): one measure of healthy weight.





Controlling Your Weight THE PROCESS OF SCIENCE

Can a Gene Make You Fat?

Several decades ago, researchers made the **observation** that a mutation in a particular gene in mice leads to a significant increase in body fat (Figure 22.21). An obvious **question** about this so-called *obese* gene is: How does a small change in DNA cause such a large change in the body? Researchers at Rockefeller University, in New York City, formed the **hypothesis** that the mutant mice become overweight because their defective *obese* gene fails to produce a protein called leptin, which helps control body weight. They made the **prediction** that injecting leptin into mutant mice would overcome the effects of the defective *obese* gene.

Their **experiment** is summarized in Figure 22.22. The researchers injected some mutant and normal mice with leptin and injected others with saline (as a control).

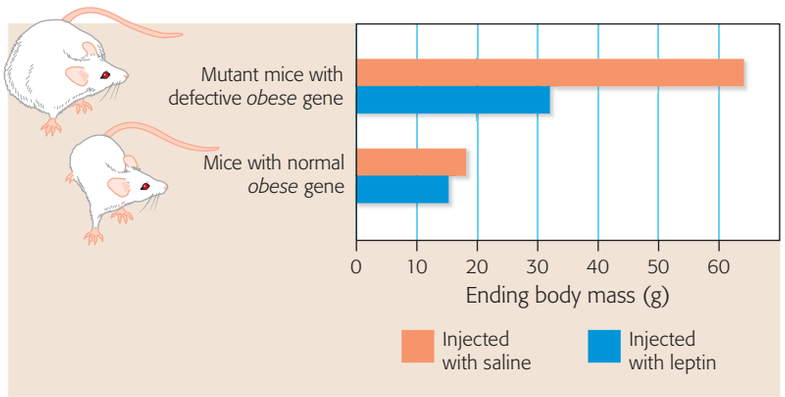
▼Figure 22.21 A ravenous rodent. The obese mouse on the left has a defect in a gene that normally produces an appetite-regulating protein.



Their **results** were striking: Mutant mice that received leptin ended the study weighing about half as much as those that received saline (compare the top two bars in Figure 22.22). Normal mice receiving leptin lost weight compared with those receiving saline, but the difference was not as large (compare the bottom two bars). The researchers concluded that leptin helps regulate body weight in mice.

How do these results apply to people? Although leptin is present in human blood, the *obese* gene is only one of more than 100 genes that contribute to the complex weight maintenance system seen in humans. So far, this complexity has prevented formulation of effective drugs to treat obesity. More important, genetics only partially explains why certain people must fight hard to control their weight, whereas others can eat all they want without gaining a pound. Genetic defects can't produce obesity without a large intake of fattening foods. The best way to maintain a healthy weight is to eat a balanced diet and get plenty of exercise.

Figure 22.22 The effect of leptin on mice with the *obese* gene. This graph shows the final average weight of normal and mutant mice after receiving injections of saline and leptin.





Controlling Your Weight EVOLUTION CONNECTION

Fat and Sugar Cravings

The majority of Americans consume too many of the high-calorie foods that contribute to obesity. Even though we all know that we need to limit the amount of fats and sugars in our diet, it sure is hard, isn't it? Most of us crave fatty or sweet foods: cheeseburgers, chips, fries, ice cream, candy. For many of us, such foods are satisfying in a way that other foods are not.

Why do we hunger for unhealthy foods? The seemingly unhelpful trait of craving fat and sugar makes more sense from an evolutionary standpoint. In the natural world, overnourishment is usually an advantage. It is only within the last 100 years that large numbers of people have had access to a reliable supply of food. For most of human history, our ancestors were continually in danger of starvation. On the African savanna, fatty or sweet foods were probably hard to find. In such a feast-or-famine existence, natural selection may have favored individuals who gorged themselves on the rare occasions when rich, fatty foods were available. With their ample reserves, they were more likely than thinner peers to survive the inevitable famines.

Perhaps our modern taste for fats and sugars reflects the advantage it conveyed in our evolutionary history. Of course, today most people typically hunt and gather in grocery stores, restaurants, and cafeterias **(Figure 22.23)**. Although we know it is unhealthful, many of us find it difficult to overcome the ancient survival behavior of stockpiling for the next famine.

Figure 22.23 Modern hunter-gatherers.



Chapter Review

SUMMARY OF KEY CONCEPTS

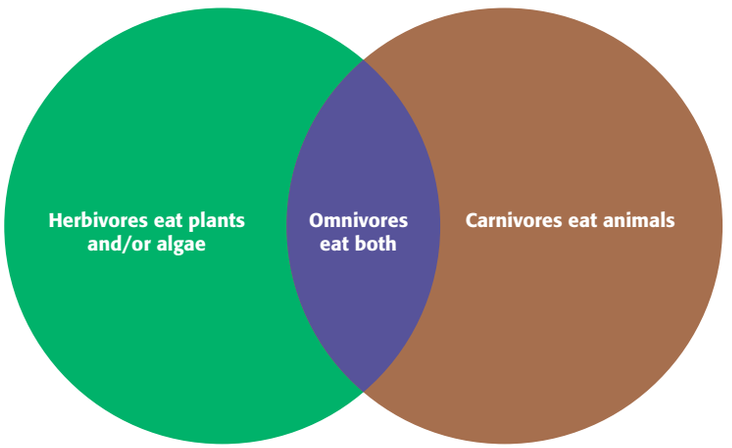
Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Overview of Animal Nutrition

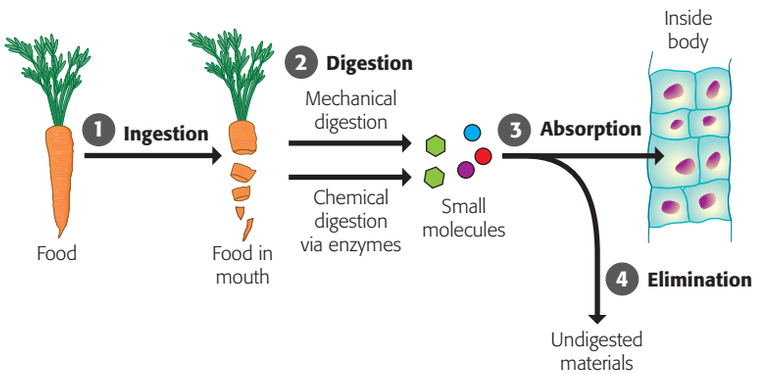
Animals must eat other organisms to obtain organic molecules for energy and building materials.

Animal Diets

Herbivores mainly eat plants and algae, carnivores mainly eat other animals, and omnivores regularly eat animals as well as plants or algae.



The Four Stages of Food Processing



Digestive Compartments

In animals, the breakdown of food occurs within food vacuoles (membrane-enclosed compartments within cells), a gastrovascular cavity (a digestive compartment with a single opening), or an alimentary canal, also called a digestive tract (a tube with two separate openings: mouth and anus).

A Tour of the Human Digestive System

System Map

Alimentary canal	Accessory organs	Digestion		Absorption
		Mechanical	Chemical	
Mouth (oral cavity)	Salivary glands	Chewing	Salivary amylase	
↓ Pharynx and esophagus				
↓ Stomach		Churning	Acid and pepsin (in gastric juice)	
↓ Small intestine	Liver, gallbladder, pancreas		Other enzymes	Nutrients and water
↓ Large intestine				Water
↓ Anus				

The Mouth, The Pharynx, The Esophagus

Within the mouth (oral cavity), teeth function in mechanical digestion, breaking food into smaller pieces. Salivary amylase, an enzyme in saliva, initiates chemical digestion by starting the breakdown of starch into sugars. The pharynx within the throat chamber leads to both the digestive and respiratory systems. When you swallow, the epiglottis closes the trachea and opens the esophagus. The esophagus connects the pharynx to the stomach and moves food along via rhythmic muscular contractions called peristalsis.

The Stomach

This elastic organ stores food, functions in mechanical digestion by churning, and uses gastric juice for chemical digestion. Mucus secreted by the cells of the stomach lining helps protect the stomach from self-digestion. Sphincters regulate the passage of food into and out of the stomach.

The Small Intestine

Small in diameter but very long, the small intestine is the main organ of chemical digestion and nutrient absorption. Most chemical digestion occurs in the duodenum, the first part of the small intestine, where chyme from the stomach mixes with pancreatic juice, bile, and a digestive juice secreted by the intestinal lining. These digestive juices include enzymes for dismantling large food molecules into small molecules. The rest of the small intestine is specialized for absorbing these small molecules. Across the large surface area of the intestinal lining, with its microvilli upon villi, intestinal cells transport nutrients into capillaries of the circulatory system.

The Large Intestine

The colon, wider and shorter than the small intestine, makes up most of the large intestine. The large intestine finishes reclaiming water that entered the alimentary canal with digestive juices. When undigested wastes reach the rectum, most water has been reabsorbed into the blood. Feces are stored in the rectum until eliminated via the anus.

Human Nutritional Requirements

Food as Fuel

Our metabolic rate depends on basal metabolic rate (energy expenditure at complete rest) plus energy burned by additional activity.

Food as Building Material

To repair and maintain tissues, we need building blocks from the breakdown of organic molecules. We also need four types of preassembled essential nutrients.

Essential Nutrients			
Essential Amino Acids	**Vitamins**	**Minerals**	**Essential Fatty Acids**
Required for protein production	Organic molecules required in very small amounts	Essential chemical elements from inorganic compounds	Required to make cell membranes

Decoding Food Labels

The U.S. Food and Drug Administration requires labels on packaged foods that list ingredients in descending order of abundance and provide information about Calories and specific nutrients.

Nutritional Disorders

Malnutrition

Malnutrition results from inadequate intake of one or more essential nutrients. Protein deficiency is the most common dietary deficiency in less industrialized countries. Malnutrition can be caused by anorexia nervosa (self-starvation) or bulimia (binge eating and purging).

Obesity

Defined as an inappropriately high ratio of weight to height, obesity is the most common nutritional disorder in most industrialized countries. About one-third of all Americans are obese, putting them at higher risk for heart disease and diabetes.

SELF-QUIZ

1. Imagine that a new species of large animal has just been discovered. Most animals have an alimentary canal, but this animal *appears* to rely entirely on food vacuoles. Why is this unlikely?
2. A friend says, "It's not eating that causes you to gain weight, it's absorption." Is that statement true?
3. _____ is the mechanical and chemical breakdown of food into small molecules, whereas _____ is the uptake of these small molecules by the body's cells.
4. Why don't astronauts in zero gravity have trouble swallowing?
5. Which class of large biological molecules is primarily broken down in the stomach? What enzyme is responsible?
6. What type of organism is responsible for most stomach ulcers? If the ulcers are detected early, how can they be treated?
7. Most chemical digestion occurs in the _____ as a result of the activity of enzymes made by the _____.
   a. stomach; oral cavity
   b. pancreas; stomach
   c. large intestine; small intestine
   d. small intestine; pancreas
8. Explain how treatment of a chronic infection with antibiotics for an extended period of time can cause a vitamin K deficiency.
9. If you maintain a normal activity level and consume the same number of calories needed for your basal metabolic rate, you will
   a. gain weight.
   b. lose weight.
   c. stay the same weight.
   d. lose weight but quickly regain it.
10. Why is the amount of oxygen you consume proportional to your metabolic rate?
11. Imagine that you and a friend both eat according to FDA nutritional guidelines, but you are a vegetarian and your friend is not. Why do you have to be more concerned about the nutritional content of your food than your friend does? What can you do to address this concern?
12. A friend takes megadoses of vitamin supplements. Which vitamin excess could pose the largest threat?
    a. A
    b. thiamin (B1)
    c. C
    d. folic acid

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

13. The FDA recommends that about 12% of our daily calories come from protein. How do we know if our diet is in accordance with those regulations? Nutritional labels typically tell how many Calories are from fat but don't specify how many Calories are from other nutrients. Proteins have approximately 4 Calories per gram. Read this cookie label and calculate the percentage of calories from protein.

Nutrition Facts
Serving Size 1 Cookie (28 g /1 oz)
Servings Per Container 8

Amount Per Serving	
Calories 140	Calories from Fat 60
	% Daily Value*
Total Fat 7g	**11%**
Saturated Fat 3g	**15%**
Trans Fat 0g	
Cholesterol 10mg	**3%**
Sodium 80mg	**3%**
Total Carbohydrate 18g	**6%**
Dietary Fiber 1g	**4%**
Sugars 10g	
Protein 2g	

14. Describe some nutritional and digestive problems a patient might face after gastric bypass surgery.

BIOLOGY AND SOCIETY

15. How could you test the claims of companies that sell weight loss supplements? Should these companies be accountable for false claims?
16. Should insurance companies pay for gastric bypass surgeries?

23 Circulation and Respiration



The demand for stamina.
Triathletes require world-class circulatory and respiratory systems to maintain their pace over extended periods.



CHAPTER CONTENTS

Unifying Concepts of Animal Circulation 496
The Human Cardiovascular System 497
Unifying Concepts of Animal Respiration 507
The Human Respiratory System 509

CHAPTER THREAD
Athletic Endurance

BIOLOGY AND SOCIETY
Avoiding "The Wall" 495
THE PROCESS OF SCIENCE
Live High, Train Low? 504
EVOLUTION CONNECTION
Evolving Endurance 513



Athletic Endurance BIOLOGY AND SOCIETY

Avoiding "The Wall"

What does it take to be an elite endurance athlete? To be sure, it takes guts, determination, and dedication. But is that all? From a biological standpoint, what it really takes to be an Iron Man is the ability to deliver a steady supply of oxygen to muscle cells over an extended period of time. So to be a marathoner or a long-distance swimmer, you must have world-class circulatory and respiratory systems.

To understand this claim, we need to understand what goes on within the body of an endurance athlete. To perform work over an extended period—over the course of a 26-mile run, for example—muscle cells require a steady supply of oxygen (O_2) and must be able to rid themselves of carbon dioxide (CO_2) waste. As long as there is enough O_2 reaching the muscle tissue and enough CO_2 being removed, well-trained athletes can perform at a steady pace for hours. What limits the speed and stamina of most endurance athletes is not the strength of their muscles but the ability of their heart and lungs to deliver oxygen at a steady rate. If the heart and lungs can't deliver enough oxygen, an athlete will hit "the wall" and be unable to continue.

It isn't surprising that endurance athletes put considerable effort into training their bodies to deliver more oxygen over longer periods of time. One way they do this is through endurance training. We all know that training for an athletic activity (say, jogging) allows us to perform the activity better and longer in the near future. Elite athletes who need a more intensive regimen often turn to high-altitude training. The lower atmospheric pressure at high altitude means that fewer molecules of O_2 are taken into the body with each breath. By training under these conditions, athletes hope that the body will adapt to need less O_2. If it does, these adaptations will make competing at normal altitude easier. Some athletes even train or sleep in low-oxygen chambers that simulate high altitudes. Still others turn to cheating by blood doping (injecting red blood cells to increase the number of them in circulation) or taking drugs that artificially increase the red blood cell count. Because red blood cells carry oxygen, having more of them aids endurance.

Properly functioning circulatory and respiratory systems are essential not just to athletes but to all of us. In fact, a failure of either system can result in rapid death. The two systems are such close partners that we will explore them in a single chapter. For each of the two systems, we'll start by considering general challenges and survey the variety of ways these are addressed. We'll then take a closer look at each system in humans. Throughout the discussion, we'll examine what may happen when these systems fail and consider medical options to maintain health.

☑ CHECKPOINT

Why can't the human body rely solely on diffusion to provide all needed chemicals to body cells?

Answer: *Diffusion is only effective over short distances. Diffusion alone would take too long to convey materials throughout the large human body.*

Unifying Concepts of Animal Circulation

Every organism must exchange materials and energy with its environment. In simple animals, such as hydras and jellies, nearly all the cells are in direct contact with the outside world. Thus, every body cell can easily exchange materials with the environment by **diffusion**, the spontaneous movement of molecules from an area of higher concentration to an area of lower concentration (see Figure 5.12). However, most animals are too large or too complex for exchange to take place by diffusion alone. In such animals, a **circulatory system** facilitates the exchange of materials, providing a rapid, long-distance internal transport system that brings resources close enough to cells for diffusion to occur. Once there, the resources that cells need, such as nutrients and O_2, enter the cytoplasm through the plasma membrane. And metabolic wastes, such as CO_2, diffuse from the cells to the circulatory system for disposal. ☑

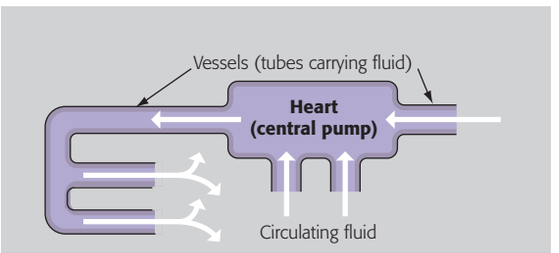
Open and Closed Circulatory Systems

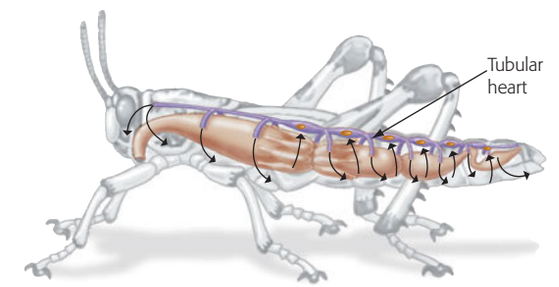
All but the simplest animals have a circulatory system with three main components: a central pump, a vascular system (a set of tubes), and a circulating fluid. Two main types of circulatory systems have evolved in animals. Many invertebrates, including most molluscs and all arthropods, have an **open circulatory system**. The system is called "open" because fluid is pumped through open-ended tubes and flows out among the cells **(Figure 23.1a)**.

Nearly all other animals have a **closed circulatory system** in which blood stays within a set of tubes and is distinct from the interstitial fluid, the fluid that fills the spaces around cells **(Figure 23.1b)**. One or more hearts pump blood into large tubes that branch into smaller ones winding through the organs. Earthworms, octopuses, and vertebrates (including humans) are some examples of animals with a closed circulatory system.

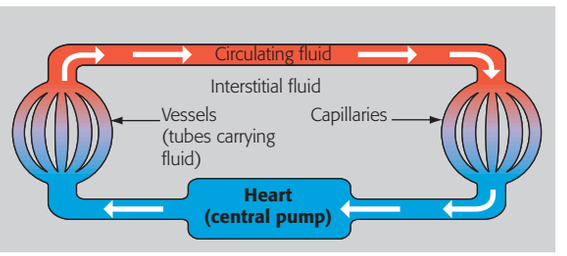
The closed circulatory system of humans and other vertebrates, consisting of a heart and blood vessels, is called a **cardiovascular system** (from the Greek *kardia*, heart, and Latin *vas*, vessel). The fish in Figure 23.1b illustrates the main features of a cardiovascular system. The heart receives blood in a chamber called the **atrium** (plural, *atria*). A second chamber called the **ventricle** pumps blood away from the heart. Blood is confined in three

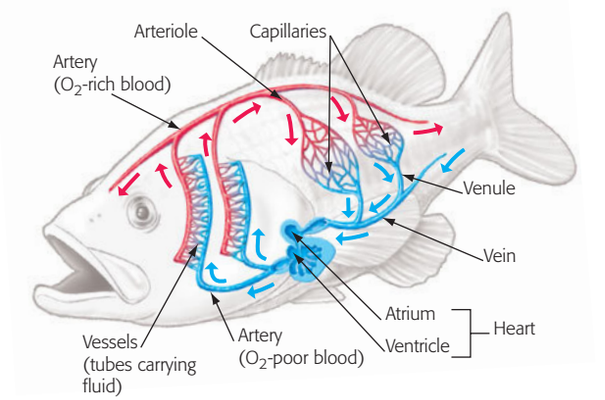
▼ Figure 23.1 Open and closed circulatory systems.





(a) Open circulatory system. In an open system, the heart pumps circulating fluid into body tissues, where nutrients diffuse directly into body cells. Contractions of body muscles move the fluid toward the tail.





(b) Closed circulatory system. In a closed system, blood is contained within vessels, separate from the interstitial fluid bathing the cells. In a fish, blood is pumped from the heart to the gills, then to capillaries in body tissues, and finally back to the heart.

main types of blood vessels: arteries, capillaries, and veins. **Arteries** carry blood away from the heart, branching into smaller **arterioles** as they approach the organs. The blood then flows from arterioles into networks of tiny vessels called **capillaries** that run through nearly every organ and tissue in the body. The thin walls of capillaries allow exchange between the blood and interstitial fluid. Capillaries are the functional center of the circulatory system: This is where materials are transferred to and from surrounding tissues. You can think of this as a kind of postal system: Many people and machines are involved in bringing your mail, but the actual transfer back and forth takes place at your mailbox. As blood flows out of the capillaries, it enters **venules**, which in turn converge into larger **veins** that return blood back to the heart, completing the circuit. ☑

☑ CHECKPOINT

Place the following in the order that describes how blood travels from the heart to cells throughout the body and back to the heart: capillaries, arteries, arterioles, venules, and veins.

Answer: *Heart → arteries → arterioles → capillaries → venules → veins → heart*

The Human Cardiovascular System

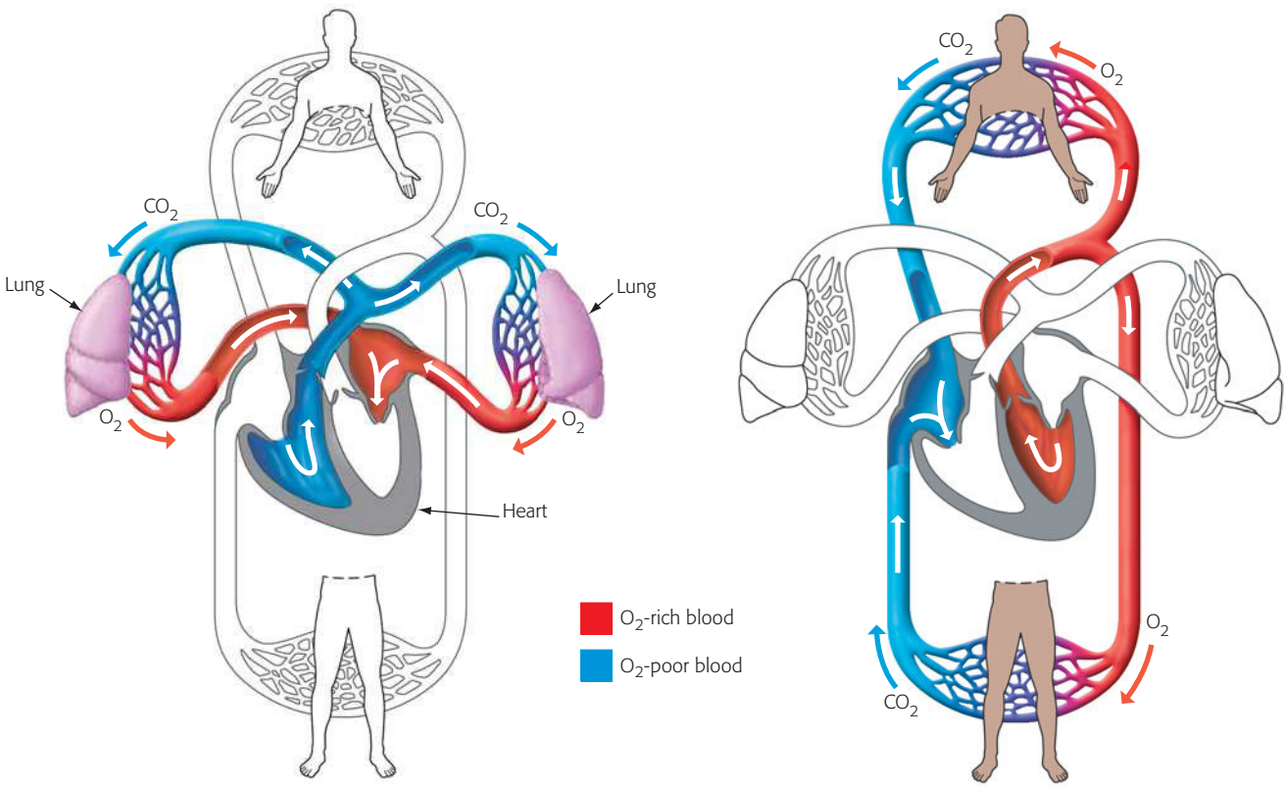
Recall that most animals have a circulatory system consisting of three main components: a pump, a vascular system, and a circulating fluid. In the human cardiovascular system, the central pump is the heart, the vascular system consists of the blood vessels, and the circulating fluid is the blood.

The Path of Blood

In humans and other terrestrial vertebrates, the cardiovascular system is organized into a **double circulation system**, with blood flowing in two loops, or circuits.

The **pulmonary circuit** carries blood between the heart and the lungs **(Figure 23.2a)**. In the lungs, carbon dioxide diffuses from the blood into the lungs, while oxygen diffuses from the lungs into the blood. The pulmonary circuit then returns this oxygen-rich blood back to the heart. As shown in **Figure 23.2b**, the **systemic circuit** carries blood between the heart and the rest of the body. The blood supplies oxygen and nutrients to body tissues and organs and picks up carbon dioxide and other wastes from them. At the end of this circuit, the oxygen-poor blood returns to the heart via the systemic circuit.

▼ **Figure 23.2 Double circulation.** It is important to note that in the body, both of these circuits work simultaneously. The pulmonary circuit sends blood to the lungs at the same time the systemic circuit sends blood to the body.



(a) Pulmonary circuit. In organisms with double circulation, the pulmonary circuit transports blood between the heart and lungs.

(b) Systemic circuit. The systemic circuit transports blood between the heart and the rest of the body.

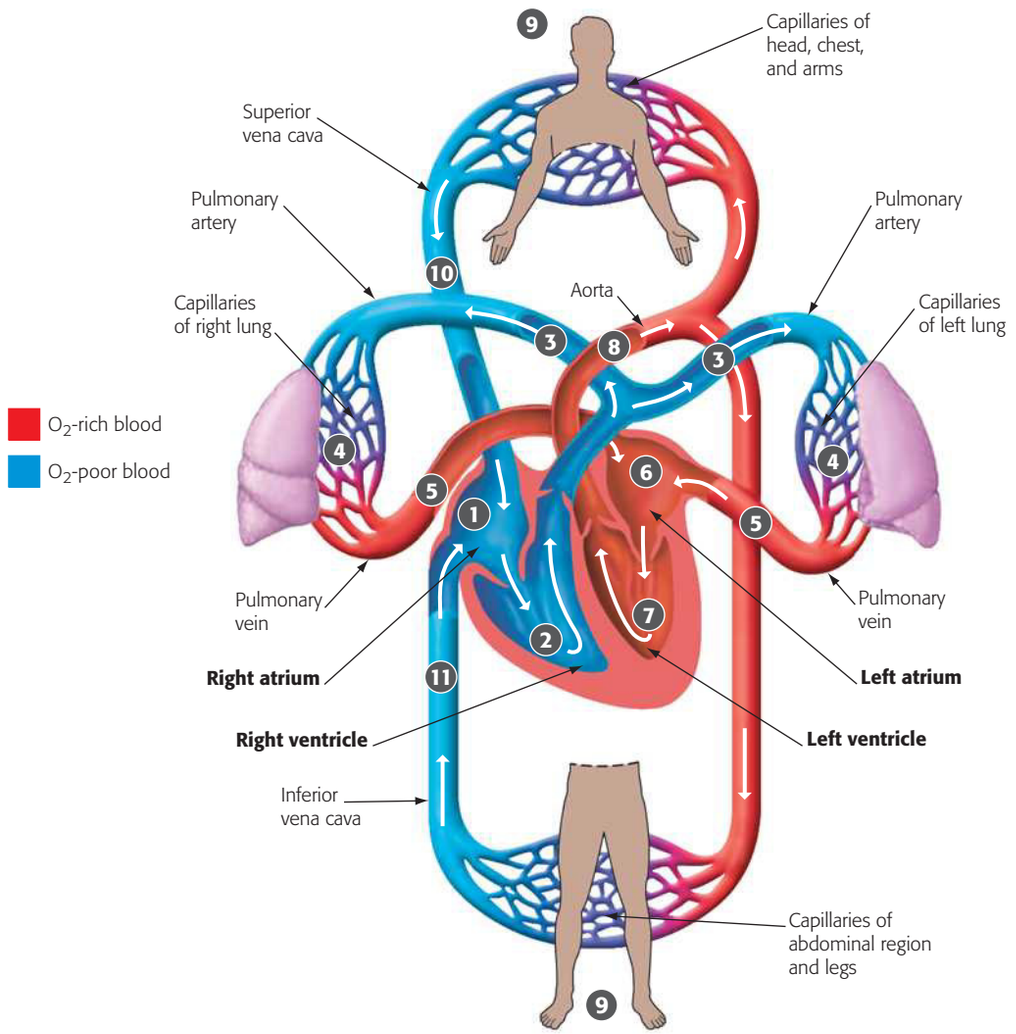
How long does it take for blood to travel from your heart to your fingertips and back?

Figure 23.3 traces the path of blood in the human cardiovascular system as it makes one complete trip around the body. The pulmonary and systemic circuits operate simultaneously: The two ventricles pump almost in unison, sending some blood through the pulmonary circuit and the rest through the systemic circuit at the same time. It takes the blood in your body about 1 minute to travel through the circulatory system—less time than it will take you to read about it!

Let's start at 1 the right atrium, where two large veins empty O_2-poor blood from the body into the heart. The blood is then pumped to 2 the right ventricle, which pumps the O_2-poor blood to the lungs via 3 two pulmonary arteries. 4 As the blood flows through capillaries in the lungs, CO_2 diffuses out of the blood and O_2 diffuses into the blood. The newly O_2-rich blood then flows through 5 the pulmonary veins to 6 the left atrium of the heart, completing the pulmonary circuit.

Next, the blood is pumped a short distance from the left atrium to 7 the left ventricle. Oxygen-rich blood leaves the left ventricle through 8 the aorta, the largest blood vessel in the body, with a diameter about as big as a quarter. Branching from the aorta are the coronary arteries that supply the heart itself and several large arteries that lead to 9 the head and arms and the abdominal region and legs. Within each organ, arteries lead to arterioles that branch into capillaries that penetrate the tissues. Diffusion of O_2 into the cells and CO_2 out of the cells takes place across the thin walls of the capillaries. Downstream, the capillaries join into venules, which convey the blood back into veins. Oxygen-poor blood from the upper body and head is channeled into 10 a large vein called the superior vena cava (in this case, "superior" means "sitting above"), and oxygen-poor blood from the lower body flows into 11 the inferior ("below") vena cava. The superior vena cava and inferior vena cava complete the systemic circuit by returning blood to the heart.

In the next section, you'll learn about the structure and function of each of the components of the human cardiovascular system and how these components work together. You may find it useful to refer back to Figure 23.3 as you learn about the details of each component. ✓



► **Figure 23.3 A trip through the human cardiovascular system.** Note that the left side of the heart is on the right side of the figure—and vice versa—because the body is viewed from the front.

✓ CHECKPOINT

In the human cardiovascular system, what is the difference between the pulmonary circuit and the systemic circuit?

Answer: The pulmonary circuit transports blood between the heart and lungs, whereas the systemic circuit transports blood between the heart and body tissues other than the lungs.

How the Heart Works

The hub of the human cardiovascular system is the **heart**, a muscular organ about the size of a fist located under the breastbone. Remember that humans have a double circulation system, with the pulmonary circuit pumping blood between the heart and lungs and the systemic circuit transporting blood between the heart and the rest of the body. This double circuit is supported by a four-chambered heart **(Figure 23.4)**.

The atria collect blood returning to the heart and pump it a short distance into the ventricles. The ventricles then pump the blood out of the heart to the other body organs. The ventricles are much more powerful than the atria (which makes sense, given their harder task). Four valves in the heart prevent backflow and keep blood moving in the correct direction. The right atrium receives oxygen-poor blood from body tissues via two large veins, and the right ventricle pumps it to the lungs. The left atrium receives oxygen-rich blood from the lungs, and the left ventricle pumps it out to body organs via the arteries. Thus, the structure of a four-chambered heart prevents oxygen-rich and oxygen-poor blood from mixing. ☑

The Cardiac Cycle

The muscles of the heart relax and contract rhythmically in what is called the **cardiac cycle**. One heart beat makes up one complete circuit of the cardiac cycle. In a healthy adult at rest, the number of beats per minute, or **heart rate**, ranges between 70 and 80. Through superior conditioning, endurance athletes can achieve resting heart rates in the 50s or 60s.

The relaxation phase of the heart cycle is known as **diastole**; the contraction phase is called **systole**. **Figure 23.5** follows the heart through a cycle, which lasts only 0.8 second. ❶ During diastole, which lasts about 0.4 second, blood returning to the heart flows into all four chambers. ❷ During the first 0.1 second of systole, the atria contract, forcing all the blood into the ventricles. ❸ In the last 0.3 second of systole, the ventricles contract, pumping blood out of the heart and into the aorta and pulmonary arteries.

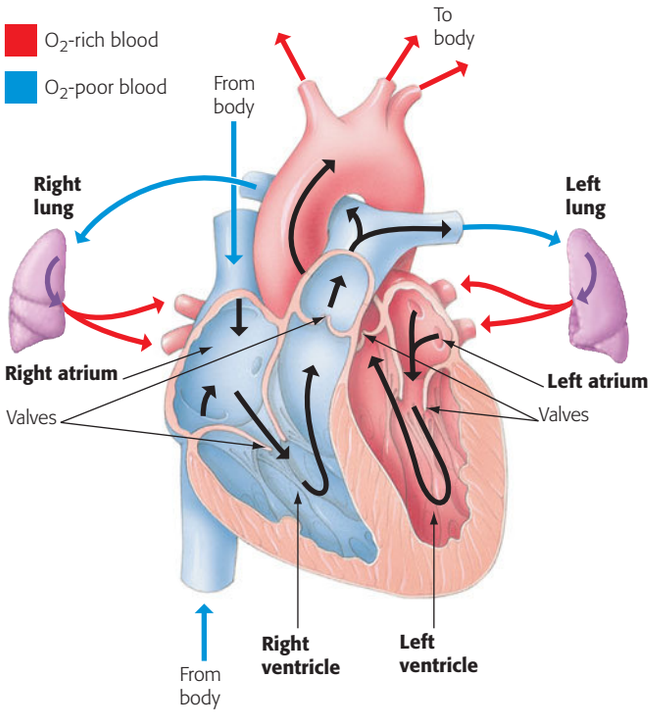
As it beats, the heart makes a distinctive "lubb-dupp, lubb-dupp" sound as the heart valves snap shut. You can hear this sound with a stethoscope or by pressing your ear against a friend's chest. A trained ear can also detect the sound of a **heart murmur**, which may indicate a defect in one or more of the valves. A serious murmur sounds like a "hisssss" as blood squirts backward through a defective valve. Some people are born with murmurs, while others have valves damaged by infection (such as rheumatic fever). Severe murmurs can reduce blood flow to the point that it causes death. However, most cases of heart murmur are not serious, and those that are can be corrected by replacing the damaged valves with artificial ones or with valves taken from an organ donor (human or other animal, usually a pig).

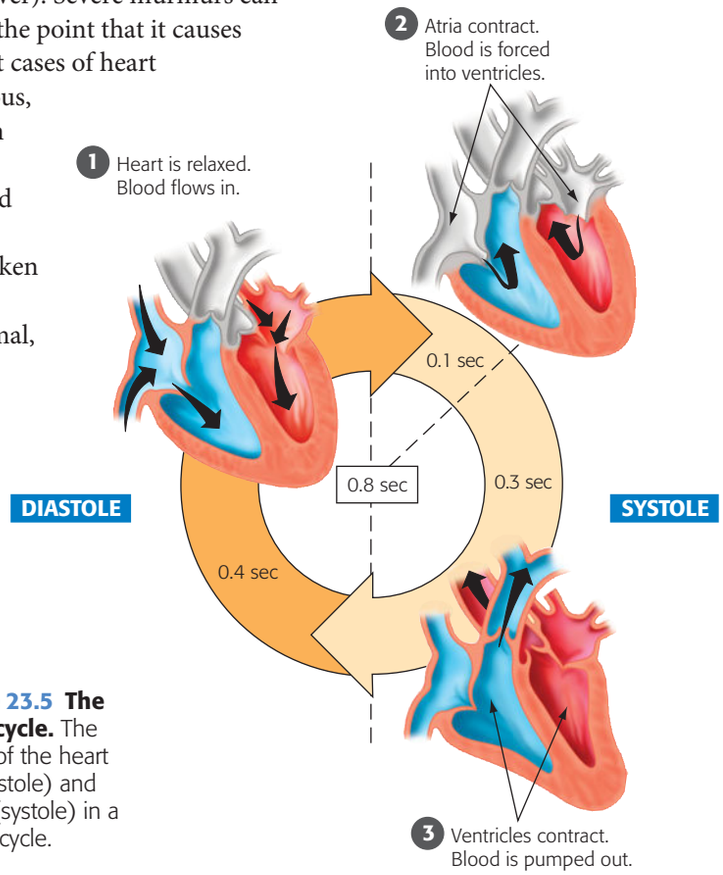
☑ CHECKPOINT

1. What kind of blood vessels carry blood away from the heart? What kind of vessels return blood to the heart?
2. Which chambers pump blood out of the heart? Which chambers receive blood returning to the heart?

Answers: **1.** *arteries; veins* **2.** *ventricles; atria*

▼ Figure 23.4 Path of blood flow through the human heart. The heart contains four chambers, with two atria located above two ventricles. Valves help maintain a one-way flow of blood. Notice that oxygen-poor blood and oxygen-rich blood do not mix.

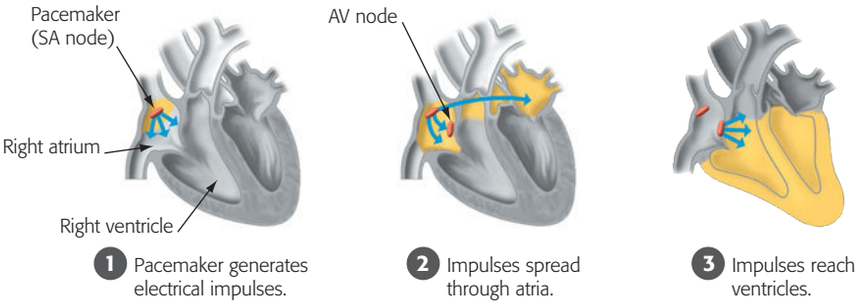




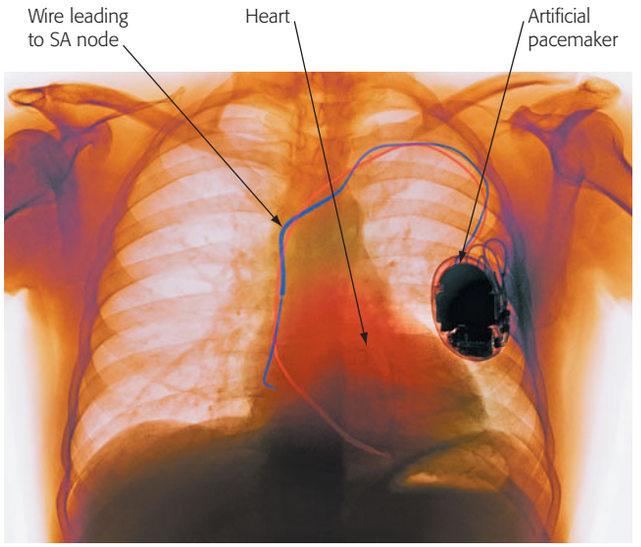
► Figure 23.5 The cardiac cycle. The muscles of the heart relax (diastole) and contract (systole) in a rhythmic cycle.

The Pacemaker and the Control of Heart Rate

All the muscle cells in your heart beat in unison under the direction of a conductor called the **pacemaker**, or **SA (sinoatrial) node** (Figure 23.6a). (Here we are referring to the body's natural pacemaker; we will discuss artificial pacemakers shortly.) 1 The pacemaker is made up of specialized muscle tissue in the wall of the right atrium that generates electrical impulses. 2 Impulses from the pacemaker spread quickly through the walls of both atria, prompting the atria to contract at the same time. The impulses then pass to a relay point called the **AV (atrioventricular) node** that delays the signals by about 0.1 second. This delay allows the atria to empty completely before the impulses are passed to the ventricles. 3 Once the impulses reach the ventricles, the ventricles contract strongly, driving the blood out of the heart.



(a) The heart's natural pacemaker. The SA (sinoatrial) node is located within the muscle tissue in the wall of the right atrium. The yellow represents how far the electrical signals have spread.



(b) Artificial pacemaker. A small electronic device surgically implanted into cardiac muscle or (as shown here) the chest cavity and connected to the SA node by a wire can help maintain the proper electrical rhythms of a defective heart.

▲ **Figure 23.6 Pacemakers.**

A variety of cues influence the signals sent by the pacemaker. For example, epinephrine (also called adrenaline), the "fight-or-flight" hormone released during times of stress, increases heart rate (see Chapter 25). Adrenaline is often injected by paramedics to help restart a stopped heart. Stimulants, such as caffeine, also make the heart beat faster. And heart rate increases with exercise, an adaptation that enables the circulatory system to provide the additional oxygen needed by muscles hard at work.

The impulses sent by the pacemaker produce electrical currents that can be detected by electrodes placed on the skin and recorded as an **electrocardiogram** (**ECG** or **EKG**). Careful reading of an EKG can provide a wealth of data about the health of the heart. During a heart attack, the heart's pacemaker is often unable to maintain a normal rhythm. Electrical stimulation by hospital defibrillators (the electrical "paddles" often seen in medical dramas) and automated external defibrillators—portable devices that analyze the heart's electrical rhythm and apply electrical shocks as needed—may be the only way to "reset" the pacemaker and restore a proper heart rhythm. In certain kinds of heart disease, the heart's self-pacing system fails to maintain a normal rhythm. The remedy is an artificial pacemaker, a small electronic device surgically implanted near the SA node. This device emits electrical signals to maintain normal heart beats (Figure 23.6b).

How does a defibrillator work?

Blood Vessels

If we think of the heart as the body's "pump," then the system of arteries, veins, and capillaries connected to it can be thought of as the "plumbing." If you review Figure 23.3, you'll notice that arteries and veins are distinguished by the direction in which they carry blood: Arteries carry blood *away from* the heart, and veins carry blood *toward* the heart. Capillaries allow for exchange between the bloodstream and the tissue cells (via interstitial fluid).

All blood vessels are lined by a thin layer of tightly packed epithelial cells. Structural differences in the walls of the different kinds of blood vessels correlate with their different functions (Figure 23.7). Capillaries have very thin walls—often just one cell thick—that allow rapid exchange of substances between the blood and the interstitial fluid that bathes tissue cells. The

smallest capillaries are so small that blood cells must pass through them single file. The walls of arteries and veins have two additional, thicker layers. An outer layer of elastic connective tissue allows the vessels to stretch and recoil. Between this layer and the epithelial cells is a middle layer of smooth muscle. By constricting or relaxing in response to signals from the brain, smooth muscle can narrow or widen the blood vessels, thereby regulating blood flow. Certain blood pressure medications work by blocking the chemicals involved in this system. This action widens the vessels, lowers blood pressure, and reduces the risk of heart attack and stroke. Veins convey blood back to the heart at low velocity and pressure after the blood has passed through capillary beds. Veins (but not arteries) also have one-way valves that prevent backflow, ensuring that blood always moves toward the heart. ☑

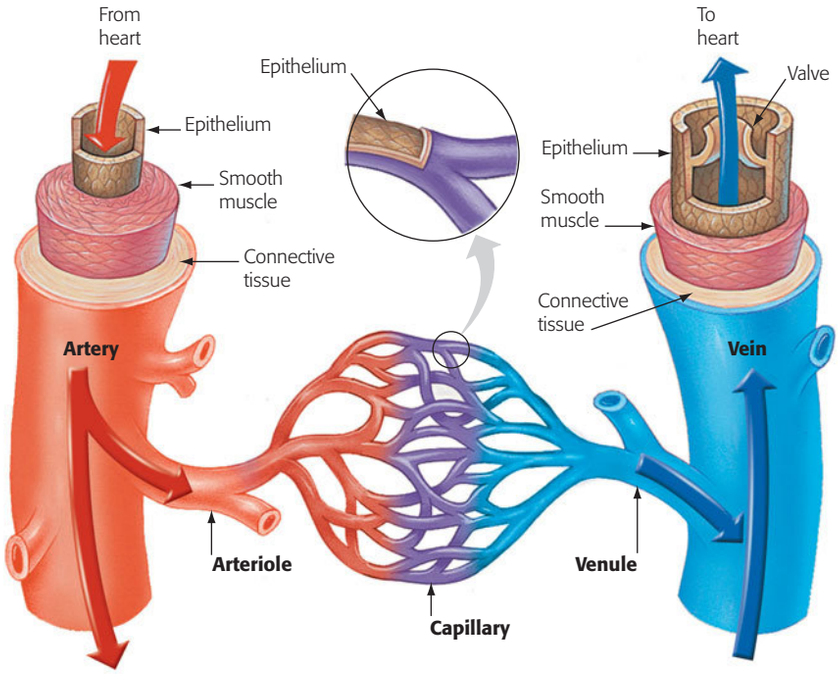
Blood Flow through Arteries

The force that blood exerts against the walls of your blood vessels is called **blood pressure**. Created by the pumping of the heart, blood pressure pushes blood from the heart through the arteries and arterioles to the capillary beds. When the ventricles contract during systole, blood is forced into the arteries faster than it can flow into the arterioles. This stretches the elastic walls of the arteries. You can feel this rhythmic stretching of your arteries when you take your **pulse**. The elastic walls of the arteries snap back during diastole, maintaining enough pressure on the remaining blood to sustain a constant flow into arterioles and capillaries. Thus, blood pressure is recorded as two numbers, such as 120/80 ("120 over 80"). The first number is blood pressure during systole (in millimeters of mercury, a standard pressure unit); the second number is the blood pressure that remains in the arteries during diastole.

Normal blood pressure falls within a range of values, but optimal blood pressure for adults is below 120 systolic and below 80 diastolic (as measured on the upper arm). Lower values are generally considered better, although very low blood pressure may lead to light-headedness and fainting. Blood pressure higher than normal may indicate a serious cardiovascular disorder.

High blood pressure, or **hypertension**, is persistent systolic blood pressure higher than 140 and/or diastolic blood pressure higher than 90. Hypertension affects approximately one-quarter of the adult population in the United States. It is sometimes called a "silent killer" because it often displays no outward symptoms for years while increasing the risks of heart disease, a heart attack, or a stroke (death of brain tissue due to lack of oxygen). To control hypertension, you can eat a heart-healthy diet, avoid smoking and excess alcohol (more than two drinks per day), exercise regularly (at least 30 minutes of moderate activity on most days), and maintain a healthy weight. If lifestyle changes don't work, there are several medications that can help lower blood pressure.

▼Figure 23.7 The structure of blood vessels. Arteries branch into smaller vessels called arterioles, which in turn branch into capillaries. Chemical exchange between blood and interstitial fluid occurs across the thin walls of the capillaries. The capillaries converge into venules, which deliver blood to veins. All of these vessels are lined by a thin, smooth epithelium. Arteries and veins have additional layers of smooth muscle and connective tissue.



Blood Flow through Capillary Beds

Muscles control the flow of blood into capillary beds, and only about 5–10% of your capillaries have a steady flow of blood running through them at any given time. Blood flows continuously through capillaries in your most vital organs, such as the brain, heart, kidneys, and liver. In many other sites, the blood supply varies as blood is diverted from one part of the body to another, depending on need. After a meal, for instance, blood flow to the digestive tract increases. During strenuous exercise, blood is shunted away from the digestive system and supplied more generously to the skeletal muscles and skin. This is one reason why heavy exercise right after eating may cause indigestion or muscle cramping (and why you shouldn't swim too soon after eating—just like mom always said).

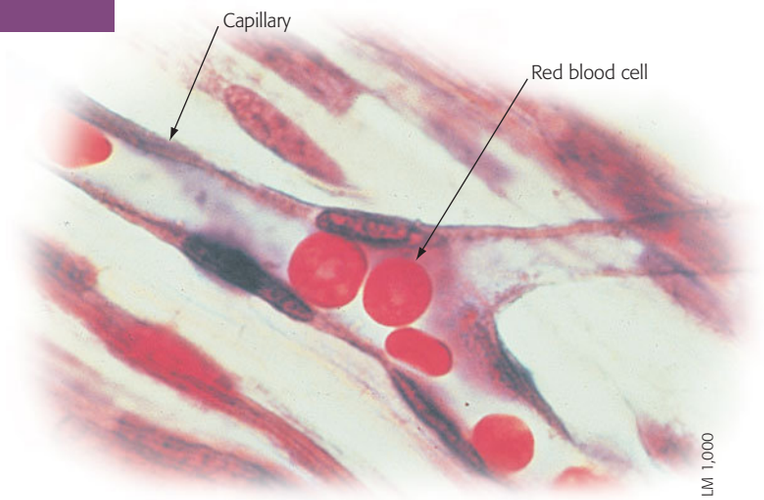
The walls of capillaries are thin and leaky. Consequently, as blood enters a capillary at the arterial end, blood pressure pushes fluid rich in O_2, nutrients, and other substances needed by the surrounding cells out of

☑ CHECKPOINT

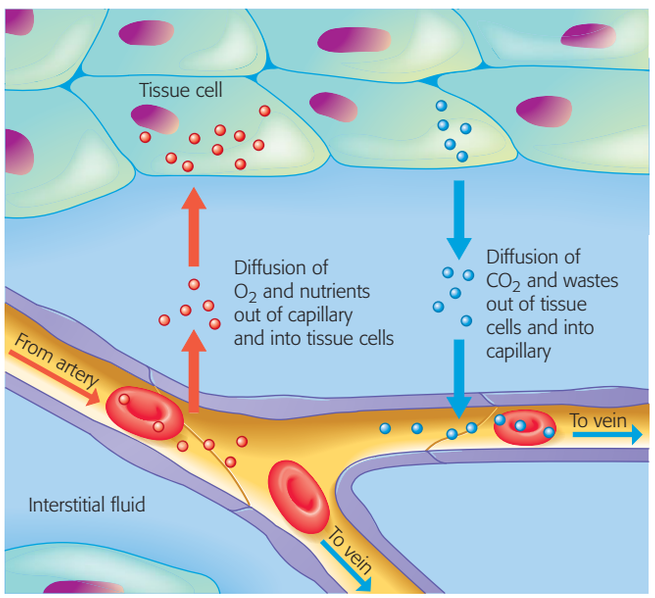
How are capillary walls an example of form fitting function?

Answer: The thinness of capillary walls helps the exchange of substances with cells.

Figure 23.8 Chemical exchange between the blood and tissue cells.



(a) Capillaries. Blood flowing through the circulatory system eventually reaches capillaries, the small vessels where exchange with cells actually takes place.



(b) Chemical exchange. Within the capillary beds, there is local exchange of molecules between the blood and interstitial fluid, which bathes the cells of tissues.

the capillary and into the interstitial fluid (Figure 23.8). These molecules then diffuse from the interstitial fluid into nearby tissue cells. Blood cells and other large components usually remain in the blood because they are too large to pass through the capillary walls. At the venous end of the capillary, CO_2 and other wastes diffuse from tissue cells, through the interstitial fluid, and into the capillary bloodstream. This local chemical exchange—between the blood and tissue cells within capillary beds—is the most important function of the circulatory system.

☑ CHECKPOINT

List the three major types of blood vessels in order of the pressure of blood within them, from highest pressure to lowest.

Answer: arteries, capillaries, veins

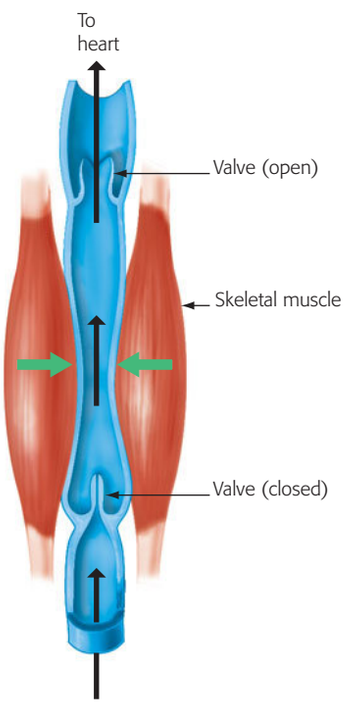
Blood Return through Veins

After chemicals are exchanged between the blood and body cells, blood flows from the capillaries into small venules, then into larger veins, and finally to the inferior and superior venae cavae, the two large blood vessels that flow into the heart. By the time blood enters the veins, the pressure originating from the heart has dropped to near zero. The blood still moves through veins, even against the force of gravity, because veins are sandwiched between skeletal muscles (Figure 23.9). As these muscles contract (when you walk, for example), they squeeze the blood along.

You may witness firsthand the importance of muscle contraction in conveying blood through your veins if you stand still for too long. After a while without contracting your muscles, you will start to become weak and dizzy and may even faint because gravity prevents blood from returning to your heart in sufficient amounts to supply your brain with oxygen.

Over time, leg veins may stretch and enlarge and the valves within them weaken. As a result, veins just under the skin can become visibly swollen, a condition called varicose veins. Besides being unsightly, varicose veins may cause serious problems, such as cramping, blood clots, and open breaks in the skin. ☑

Figure 23.9 Blood flow in a vein. The contraction of muscles surrounding veins squeezes blood toward the heart. Flaps of tissue in the veins act as one-way valves, preventing backflow.



Blood

Now that we have examined the structures and functions of the heart and blood vessels, let's focus on the composition of blood itself **(Figure 23.10)**. The circulatory system of an adult human has about 5 L (11 pints) of blood. Just over half this volume consists of a yellowish liquid called **plasma**. Plasma is about 90% water. The other 10% of plasma is made up of dissolved salts, proteins, and various other molecules being transported by the blood, such as nutrients, wastes, and hormones. Suspended within the plasma are three types of cellular elements: red blood cells, white blood cells, and platelets. Let's examine each of them in turn.

If you donate a pint of blood, how much do you have left?

Red Blood Cells and Oxygen Transport

Red blood cells, also called **erythrocytes**, are by far the most numerous type of blood cell. There are about 25 trillion of these cells in the average person's bloodstream. Carbohydrate-containing molecules on the surface of red blood cells determine a person's blood type, such as A, B, AB, or O (see Figure 9.20).

Each red blood cell contains approximately 250 million molecules of **hemoglobin**, an iron-containing protein that transports oxygen. As red blood cells pass through the capillary beds of your lungs, oxygen diffuses into the red blood cells and binds to the hemoglobin. This process is reversed in the capillaries of the systemic circuit, where the hemoglobin unloads its cargo of oxygen to the body's cells.

Human red blood cells are shaped like disks with indentations in the middle, increasing the surface area available for gas exchange (see Figure 23.10). In addition to their shape, the red blood cells of mammals have another feature that enhances their oxygen-carrying capacity: They lack nuclei and other organelles, leaving more room to carry hemoglobin. Red blood cells are also very small relative to other cells. Therefore, a population of red blood cells has a greater total surface area for gas exchange than the same volume of larger cells.

Adequate amounts of hemoglobin and red blood cells are essential to the normal functioning of the body. **Anemia** is a condition in which there is an abnormally low amount of hemoglobin or a low number of red blood cells. An anemic person feels constantly tired and run-down because the body cells do not get enough oxygen. Anemia can result from a variety of factors, including excessive blood loss, vitamin or mineral deficiencies, and certain cancers. A mutation in the gene for hemoglobin may result in sickle-cell disease, another cause of anemia (see Chapter 9).

The production of red blood cells in the bone marrow is controlled by a feedback system that monitors the amount of oxygen reaching tissues via the blood. If the tissues are not receiving enough oxygen, the kidneys produce a hormone called erythropoietin (EPO) that boosts the bone marrow's production of oxygen-carrying red blood cells. Doctors prescribe synthetic EPO to relieve the symptoms of anemia.

Because additional red blood cells boost the functions of the circulatory and respiratory systems, EPO increases athletic stamina, potentially offering a huge advantage in long athletic competitions. Thus, some endurance athletes have abused synthetic EPO in an attempt to gain an artificial advantage. EPO abuse, one

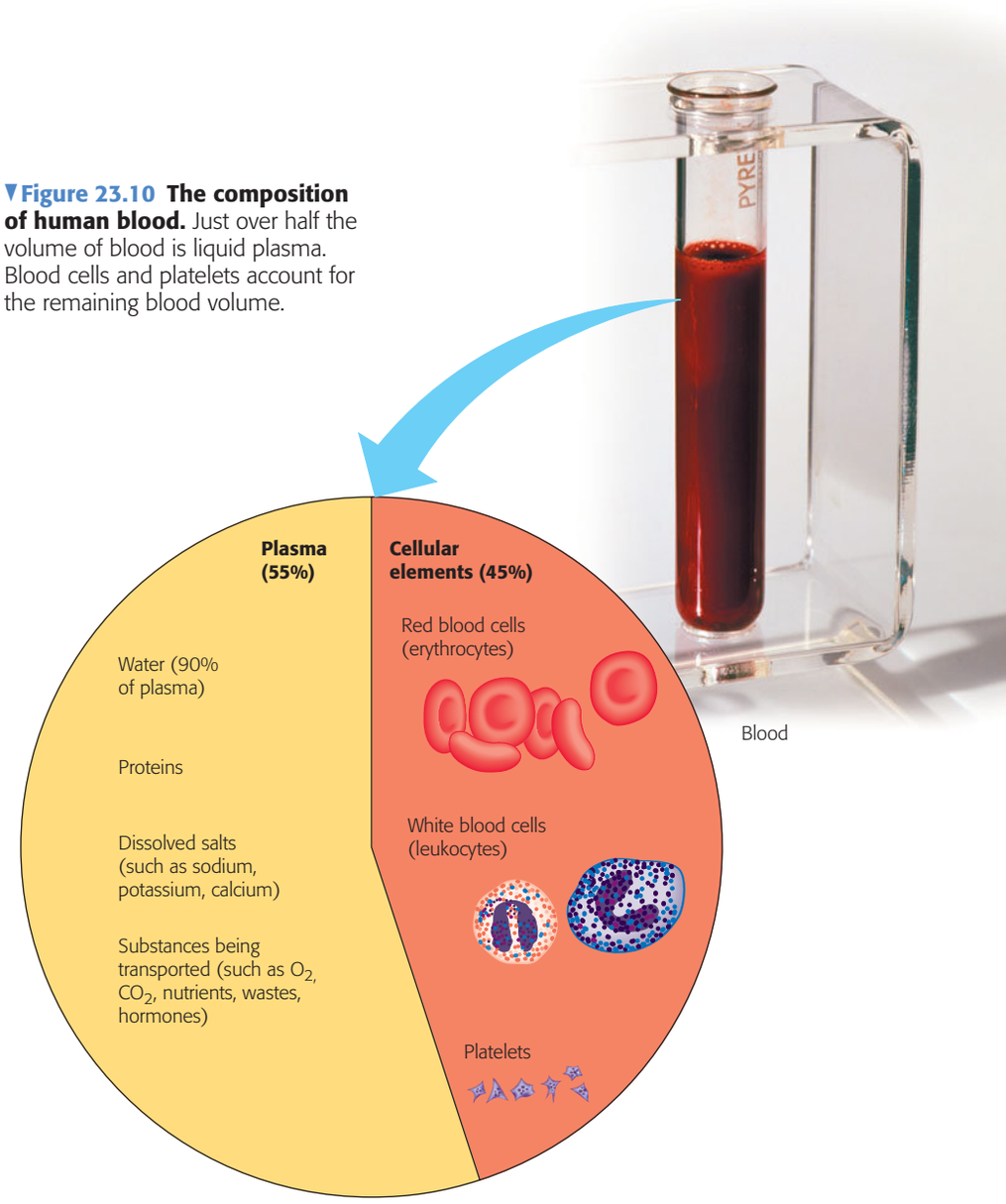


Figure 23.10 The composition of human blood. Just over half the volume of blood is liquid plasma. Blood cells and platelets account for the remaining blood volume.

type of "blood doping," is difficult to detect because it is a hormone produced naturally by the body and because synthetic EPO is rapidly cleared from the bloodstream. One way that athletic commissions test for cheaters is by measuring the percentage of red blood cells in the blood volume. A value of more than 50% is usually grounds for disqualification. EPO is banned not only because it confers an unfair advantage but also because it is dangerous: It has been blamed for the deaths of dozens of professional athletes. Fortunately, there are other, healthier ways to achieve an increase in performance, as we'll see next.



Athletic Endurance THE PROCESS OF SCIENCE

Live High, Train Low?

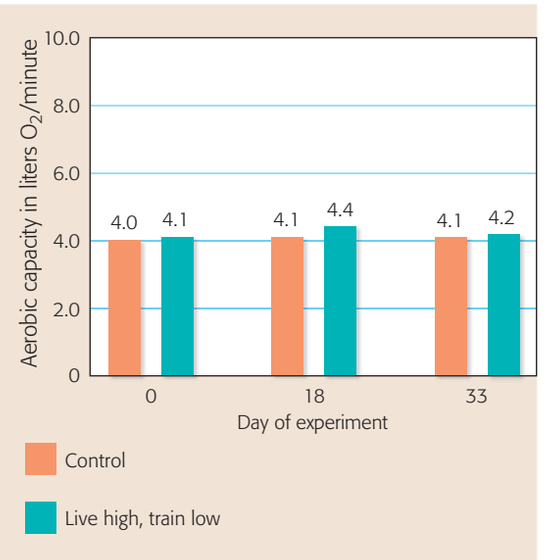
Exercise physiologists have known for years that properly designed training regimens can vastly improve the performance of endurance athletes. Athletes have learned from **observation** that it is difficult to train at low altitude (near sea level) and then compete at high altitude. This is because the air at high altitudes is at a lower pressure and therefore "thinner," with fewer molecules of oxygen taken in per breath, making it more difficult for the body to supply the O_2 needed for muscles to function properly. But if an athlete stays at high altitude for weeks or months, the kidneys will compensate by boosting production of EPO, resulting in more red blood cells, which in turn can carry more oxygen.

For the last few decades, the International Olympic Committee has sponsored research that asks the **question**: Will athletes who train at high altitude increase their performance when at lower altitudes? One leading **hypothesis** can be summed up by the phrase "live high, train low." This hypothesis holds that living at high altitudes will boost red blood cell production, which can then improve stamina during competition at lower altitudes. One **experiment** published in 2006 involved 11 elite runners as test participants. Five of these athletes lived for 18 days in rooms that were gradually adjusted to simulate an altitude of 3,000 m (nearly 2 miles, about twice the elevation of Denver), while the other six athletes lived at 1,200 m. All the athletes trained at 1,200 m.

At the start of the study (day 0), the **results** of endurance tests showed that both groups were similar in their aerobic capacity, a measure of the body's ability to take in and use oxygen (**Figure 23.11**, first pair of bars). But by the end of the training regimen (day 18), the "live high, train low" group had a higher aerobic capacity (middle pair of bars) that gradually fell over two weeks (day 33, third pair of bars). These results, as well as those from many other similar studies, are providing a scientific basis for new training regimens aimed to improve the performance of today's endurance athletes.

▼Figure 23.11 Live High, Train Low. The results of this study suggest that living at high altitude while training at low altitude can improve athletic performance, but the effect fades.





White Blood Cells and Defense

Red blood cells are just one of the cellular components of blood (Figure 23.12). As a group, **white blood cells**, or **leukocytes**, fight infections. White blood cells are larger than red blood cells and they lack hemoglobin but contain nuclei and all other organelles. There are about 700 times fewer white blood cells than red blood cells, although their numbers temporarily increase when the body is combating an infection.

Platelets and Blood Clotting

Although you get cuts and scrapes, you do not bleed to death because your blood contains two components that help form clots: platelets and fibrinogen. **Platelets** are bits of membrane-wrapped cytoplasm pinched off from larger cells in the bone marrow. Clotting begins when the tissue lining a blood vessel is damaged. Almost immediately, platelets adhere to the damaged tissue to form a sticky cluster that seals minor breaks. Platelets also release clotting factors, molecules that convert **fibrinogen**, a protein found in the plasma, to a threadlike protein called **fibrin**. Molecules of fibrin form a dense network to create a patch (see the inset in Figure 23.12). On the skin, such clots are called scabs.

The clotting mechanism is so important that any defect in it can be life-threatening. In the disease hemophilia, a genetic mutation in a gene for a clotting factor results in excessive, sometimes fatal bleeding. Too much clotting can also be fatal. An embolus is a blood clot that forms within a blood vessel but then dislodges from its point of origin and travels in the blood. If an embolus lodges in an artery of the heart and is large enough to block it, a heart attack occurs. Similarly, an embolus in the head can cause a stroke. Aspirin and heparin are anticoagulant drugs that prevent undesirable clotting in patients at risk for an embolus. ✓

Stem Cells and the Treatment of Leukemia

The red marrow inside some of your bones contains stem cells that differentiate into red and white blood cells as well as into the cells that produce platelets. (Recall from Chapter 11 that stem cells have the potential to differentiate into other types of cells.) After forming in the early embryo, these stem cells continually reproduce themselves and create all the blood cells needed throughout life. Bone marrow stem cells show great promise for the treatment of disease, particularly leukemia.

Leukemia is cancer of the white blood cells (leukocytes). Because cancerous cells grow uncontrollably, a person with leukemia has an unusually high number of white blood cells, most of which are defective. The overabundant cells crowd out the normal bone marrow cells that produce red blood cells and platelets, causing severe anemia and impaired clotting.

Some cases of leukemia do not respond to standard cancer treatments—radiation and chemotherapy. An alternative treatment involves completely destroying cancerous bone marrow and replacing it with healthy bone marrow. Marrow from the patient is harvested, processed to remove as many cancerous cells as possible, and then reinjected. Alternatively, a matching donor, often a sibling, may provide marrow.

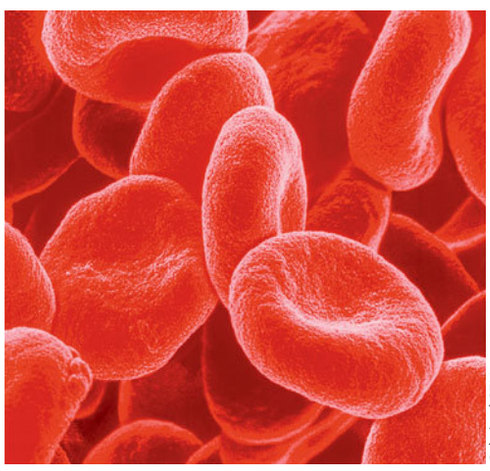
✓ CHECKPOINT

Which blood cells carry oxygen? Which provide immunity? What cellular element is needed for clotting?

Answers: red blood cells (erythrocytes); white blood cells (leukocytes); platelets

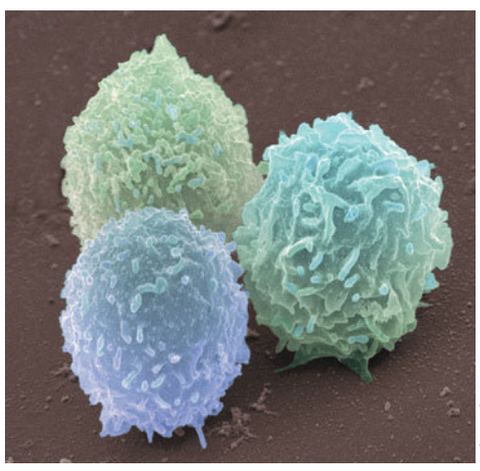
CELLULAR COMPONENTS OF BLOOD

Red Blood Cells
(cells that carry oxygen)



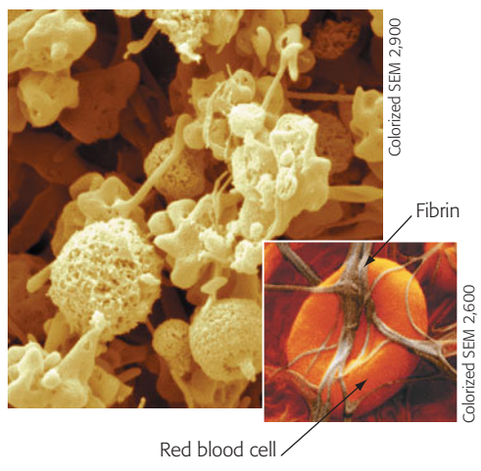
This electron micrograph shows the indented disk shape of human red blood cells.

White Blood Cells
(cells that fight infection)



This electron micrograph shows lymphocytes, a type of white blood cell.

Platelets
(bits of membrane-enclosed cytoplasm that aid clotting)



Platelets help produce a clotting protein called fibrin (shown at bottom wrapping around a red blood cell).

▲ **Figure 23.12** **The three cellular components of blood.**

Cardiovascular Disease

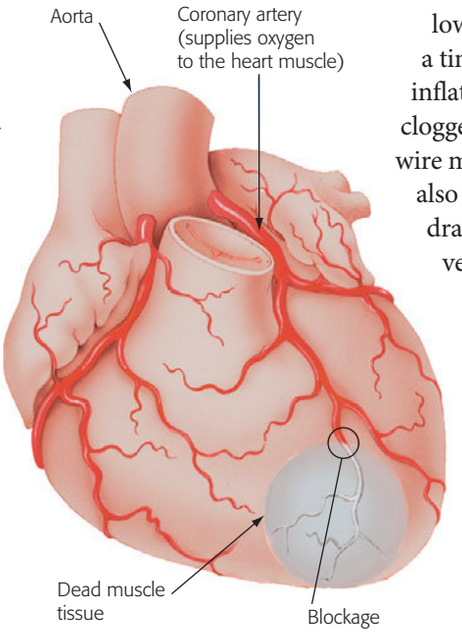
The circulatory system performs several homeostatic functions that help maintain relatively constant internal conditions. First, by exchanging nutrients and wastes with the interstitial fluid, the circulatory system helps control the chemical balance of the fluid that surrounds cells. Second, the circulatory system helps control the composition of the blood by continuously moving it through organs, such as the lungs, liver, and kidneys, that regulate the blood's contents. The circulatory system is also involved in the body's temperature regulation, hormone distribution, and defense against foreign invaders—all topics that are discussed in other chapters.

What happens when the circulatory system cannot perform its normal functions? **Cardiovascular disease**, diseases of the heart and blood vessels, accounts for 40% of all deaths in the United States, killing more than 1 million people each year. Like all of your cells, your heart muscle cells require oxygen-rich blood to survive. When blood exits the heart, several **coronary arteries** (shown in dark red in **Figure 23.13**) immediately branch off the aorta to feed the heart muscle. If one or more of these blood vessels become blocked, heart muscle cells quickly die from lack of O_2 (gray area in Figure 23.13). As noted earlier, such an event, and the subsequent failure of the heart to function properly, is called a heart attack. (The medical term is myocardial infarction, meaning "death of heart muscle tissue.") Approximately one-third of heart attack victims die almost immediately. For those who survive, the ability of the damaged heart to pump blood may be seriously impaired for life because heart muscle cannot be replaced or repaired.

What happens during a myocardial infarction?

The suddenness of a heart attack belies the fact that the arteries of most victims became impaired gradually by a chronic cardiovascular disease called **atherosclerosis**. During the course of the disease, fatty deposits called plaque develop in the inner walls of arteries, clogging the passages through which blood can flow **(Figure 23.14)**. Vessels narrowed by plaque increase blood pressure and can more easily form and trap clots. If a coronary artery becomes partially blocked, a person may feel occasional chest pain, a condition called angina.

▼Figure 23.13 Blockage of a coronary artery, resulting in a heart attack. If one or more coronary arteries become blocked, the heart muscle cells that they feed will die from lack of oxygen. Such an event, called a heart attack, can lead to permanent damage of the heart muscle.

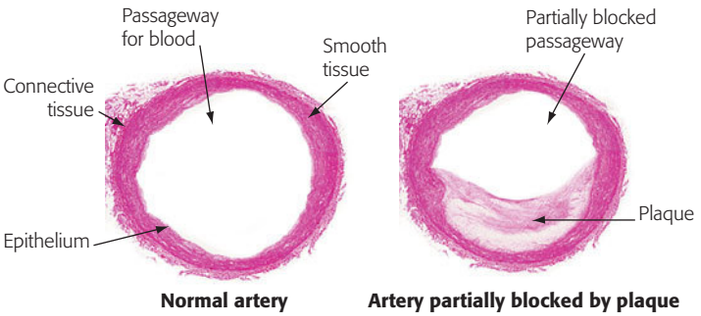


To some extent, the tendency to develop cardiovascular disease is inherited. However, three everyday behaviors significantly impact the risk of cardiovascular disease and heart attack. Smoking doubles the risk of heart attack and increases the severity if one does occur. Regular exercise (particularly "cardio" or "aerobic" workouts) can cut the risk of heart disease in half. Eating a heart-healthy diet, low in cholesterol, trans fats, and saturated fats (see Chapter 3) and high in fruits, vegetables, and whole grains can reduce the risk of developing atherosclerosis.

If a person already has cardiovascular disease, there are treatments available. Certain drugs can lower cholesterol. Angioplasty (inserting a tiny catheter with a balloon that is inflated to compress plaque and widen clogged coronary arteries) and stents (small wire mesh tubes that prop open arteries) can also help. Bypass surgery is a much more drastic remedy. In this procedure, blood vessels removed from a patient's legs are sewn onto the heart to shunt blood around clogged coronary arteries. In an even more drastic measure, a defective heart can be replaced by a transplant or even with an artificial heart (although no one has survived long with an artificial heart). Unfortunately, surgery of any kind only treats the disease symptoms, not the underlying causes, so problems will return if risk factors are not minimized.

On the bright side, the death rate from cardiovascular disease in the United States has been cut in half during the past 50 years. Health education, early diagnosis, and reduction of risk factors, particularly smoking, are mostly responsible. ✓

▼Figure 23.14 A normal artery and an artery showing atherosclerosis.



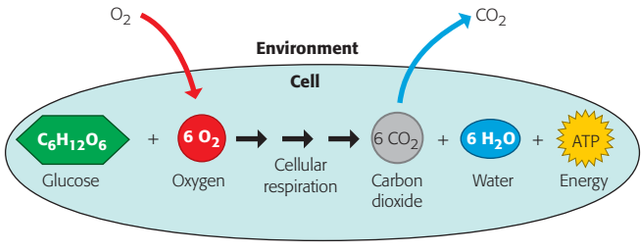
✓ CHECKPOINT

Name three things you can do to lower your risk of cardiovascular disease.

Answer: eat a heart-healthy diet, exercise regularly, and avoid smoking

Unifying Concepts of Animal Respiration

Your survival depends on close cooperation between the circulatory and respiratory systems. The circulatory system transports gases and other substances to and from body cells. Recall that within all cells, the process of cellular respiration (the topic of Chapter 6) uses oxygen and glucose to produce water, carbon dioxide, and energy in the form of ATP. All working cells therefore require a steady supply of O_2 from the environment and must continuously dispose of CO_2:



The **respiratory system** consists of several organs that facilitate exchange of O_2 and CO_2 between cells and the environment. (Note that in the context of a whole organism, the word *respiratory* refers to the process of breathing, not to cellular respiration.) ☑

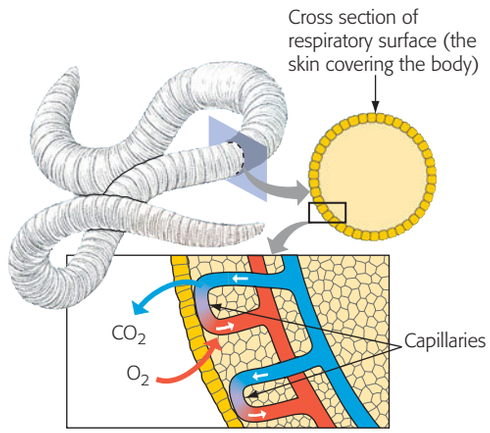
The Structure and Function of Respiratory Surfaces

Earth's main reservoir of oxygen is the atmosphere, which is about 21% O_2. Terrestrial animals access this oxygen by breathing air. Oceans, lakes, and other bodies of water also contain O_2 in the form of dissolved gas, but it makes up only 3–5% of that environment. Many aquatic animals obtain oxygen by passing water over their gills. The part of an animal where O_2 from the environment diffuses into living cells and CO_2 diffuses out to the surrounding environment is called the **respiratory surface**. The respiratory surface is usually covered with a single layer of living cells that is thin enough and moist enough to allow rapid diffusion between the body and the environment. It must be large enough to take up O_2 for every cell in the body.

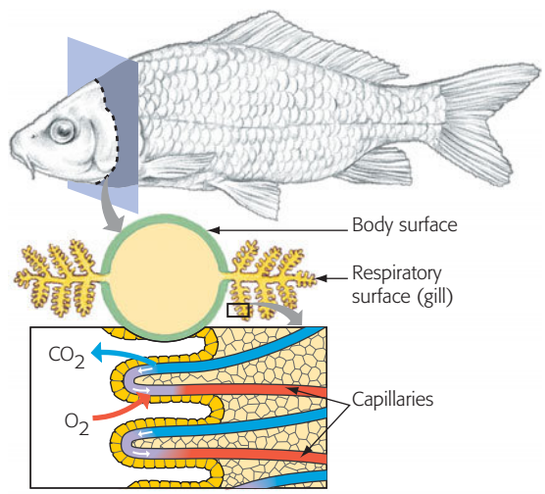
Within the animal kingdom, a variety of respiratory surfaces have evolved. For some animals, such as sponges and flatworms, the plasma membrane of every cell in the body is close enough to the outside environment for gases to diffuse in and out. In many animals, however, the bulk of the body does not have direct access to the outer environment, and the respiratory surface is the place where the environment and the blood meet. The blood then transports gases to and from the rest of the body.

Some animals use their entire outer skin as a respiratory surface. An earthworm, for example, has moist skin, and gases diffuse across its whole body surface. This results in an exchange of O_2 and CO_2 between the environment and a dense net of capillaries just below the earthworm's skin **(Figure 23.15a)**. Earthworms and other skin-breathers (such as frogs) must live in wet environments because their entire body surface must stay moist for this exchange to occur. For most animals, however, the outer body surface is either impermeable to gases or lacks sufficient area to exchange gases for the whole body. In such animals, specialized regions of the body have extensively folded or branched surfaces that provide a large surface area for gas exchange.

Gills are found in most aquatic animals, such as lobsters, which are invertebrates, and fishes, which are vertebrates. The feathery gills located on either side of a fish's head have a respiratory surface area much greater than the rest of the body surface. A fish obtains oxygen by continuously pumping water over its gills. As water passes over the respiratory surface of the gills, gases diffuse between the water and the blood. The blood then carries oxygen to the rest of the body **(Figure 23.15b)**. Gills—especially those of large, active fishes such as tuna—must be very efficient to obtain enough oxygen from water. Indeed, some aquatic animals can remove more than 80% of the oxygen from the water moving over their gills. In comparison, human lungs extract only about 25% of the oxygen in air.



(a) Skin. Some small animals, such as earthworms, use their entire moist outer skin as a respiratory organ.



(b) Gills. Fishes and many other aquatic animals have gills, feathery respiratory surfaces that extend into the surrounding water.

► **Figure 23.15 Respiratory surfaces: skin and gills.** The yellow areas represent respiratory surfaces. The boxed enlargements show a portion of the respiratory surface in the process of exchanging O_2 and CO_2.

☑ CHECKPOINT

Why do all human cells require a continuous supply of O_2 and disposal of CO_2?

Answer: O_2 is required for cellular respiration, which generates ATP for cellular work and also produces CO_2 as a waste product.

☑ CHECKPOINT

In what basic way do insects carry out gas exchange differently from the way fishes and humans do?

Answer: The respiratory system of insects uses tracheae that bring O_2 directly to body cells and carry CO_2 back directly away; fishes and humans have a circulatory system that transports O_2 from the respiratory surface to body cells and CO_2 back.

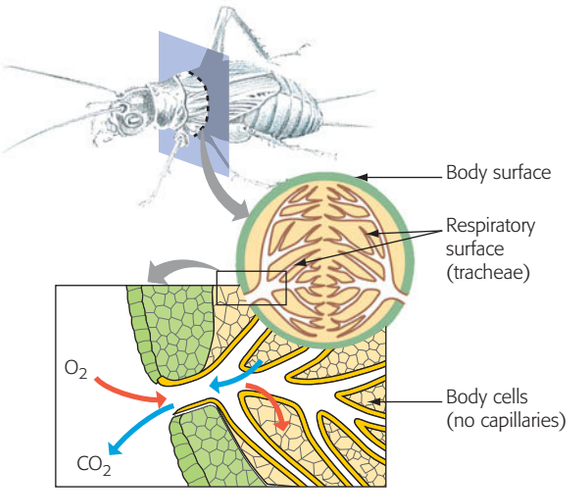
In most land-dwelling animals, the respiratory surfaces are folded into the body rather than extending from it. The infolded surfaces are open to the air only through narrow tubes. This anatomical arrangement means that only those respiratory cells needed for gas exchange must be kept moist, rather than the entire body surface (as in earthworms or frogs). The two types of respiratory structures seen in land-dwelling animals are tracheal systems and lungs.

Insects breathe using a **tracheal system**, an extensive network of branching internal tubes called tracheae **(Figure 23.16a)**. Tracheae begin near the body's surface and branch down to narrower tubes that extend to nearly every cell. Gas exchange with cells occurs via diffusion across the moist epithelium that lines the tips of the tubes. Because almost every body cell is near the respiratory surface, gas exchange in insects requires no assistance from the circulatory system.

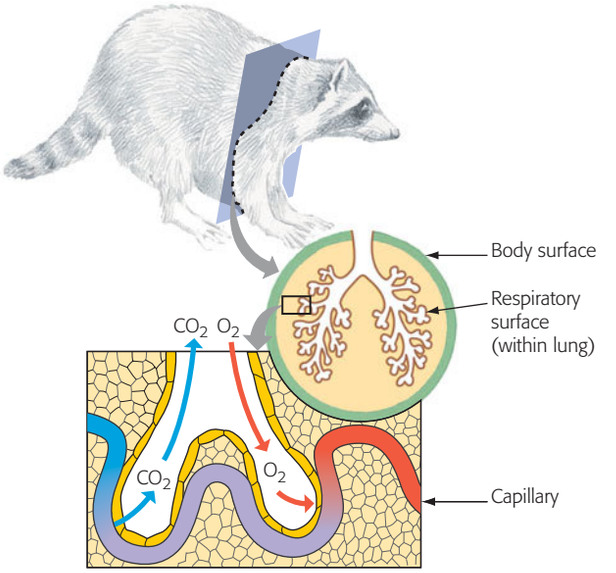
Lungs are the most common respiratory surface among snails, some spiders, and terrestrial vertebrates such as amphibians, birds and other reptiles, and mammals. In contrast to tracheae, which branch throughout an insect's body, **lungs** are localized organs lined with moist epithelium **(Figure 23.16b)**. Gases are carried between the lungs and the body cells by the circulatory system.

Figure 23.17 summarizes the different types of respiratory organs we discussed in this section. In the next section, we'll take a closer look at human lungs. ☑

► **Figure 23.16 Respiratory surfaces: tracheae and lungs.** The yellow areas represent respiratory surfaces. The boxed enlargements show a portion of the respiratory surface in the process of exchanging O_2 and CO_2.

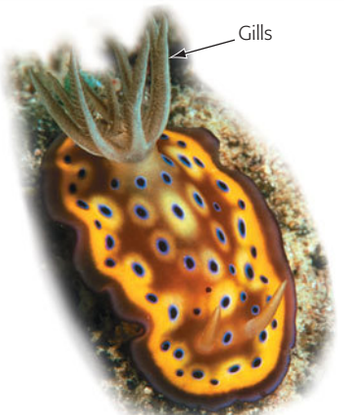
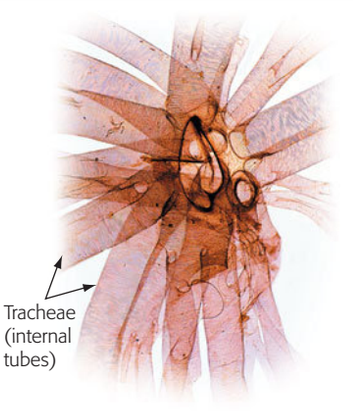
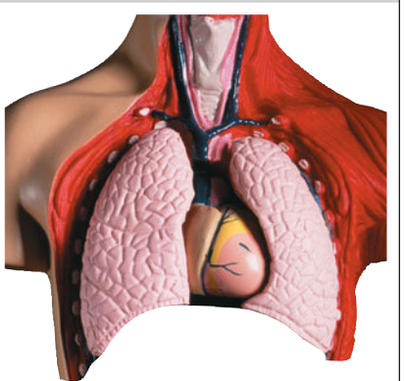


(a) Tracheae. Terrestrial insects have a pervasive system of internal tubes called tracheae that channel air directly to cells.



(b) Lungs. Most terrestrial vertebrates exchange gases across the thin lining of lungs, internal organs with a rich blood supply.

▼ **Figure 23.17 Types of respiratory organs.**

RESPIRATORY ORGANS			
Skin (entire body surface)	**Gills** (extensions of the body surface)	**Tracheae** (branching internal tubes)	**Lungs** (localized internal organs)
			
Moist skin of a leech	Gills of a sea slug	Tracheae of a silk moth caterpillar	Model of a pair of human lungs

The Human Respiratory System

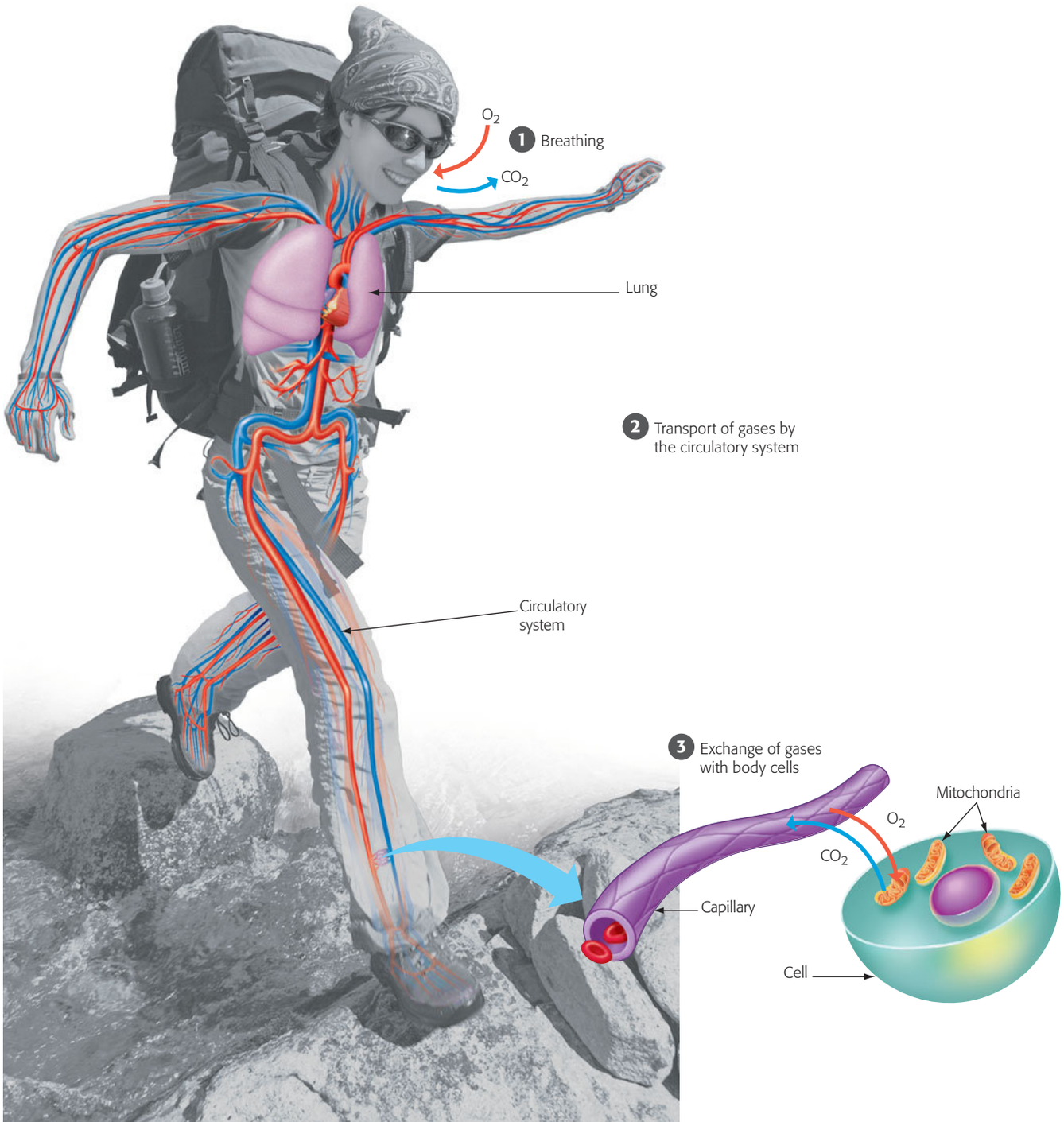
Figure 23.18 provides an overview of three phases of gas exchange in humans. 1 The first step of gas exchange is **breathing**, the ventilation of the lungs by alternate inhalation and exhalation. When an animal with lungs breathes, a large, moist internal surface is exposed to air. Oxygen diffuses across the cells lining the lungs and into the surrounding blood vessels. Simultaneously, CO_2 passes out of the blood vessels, into the lungs, and is exhaled. Most land animals require a lot of oxygen. The inner tubes of the lungs are extensively branched, providing a large respiratory surface. 2 The second step in gas exchange is the transport of O_2 from the lungs to the rest of the body via the circulatory system. The blood also carries CO_2 from the tissues back to the lungs. 3 In the final step of gas exchange, O_2 diffuses from red blood cells into body cells, which release CO_2 into the blood. The delivered O_2 is used by the body cells to obtain energy from food via the process of cellular respiration. This same process produces CO_2 as a waste product that cells pass to the blood. The circulatory system transports the CO_2 back to the lungs, where it is exhaled. ☑

☑ CHECKPOINT

Which type of cellular transport is responsible for moving respiratory gases between the circulatory system and the rest of the body?

Answer: *diffusion*

▼Figure 23.18 The three phases of gas exchange.



The Structure and Function of the Human Respiratory System

Figure 23.19a shows the human respiratory system. Our lungs are located in the chest cavity, protected by the rib cage and bordered along the bottom by the **diaphragm**, a sheet of muscle. Let's get an overview of the respiratory system by following the flow of air into the lungs.

Air enters the respiratory system through the nostrils and mouth. In the nasal cavity, the air is filtered by hairs and mucus, warmed, humidified, and sampled by smell receptors. The air passes to the **pharynx**, where the digestive and respiratory systems meet. If a piece of food lodges in your pharynx, blocking passage of air to your lungs, you can choke and quickly die. Learning the Heimlich maneuver (quick thrusts to the diaphragm to compress the lungs and force air upward through the trachea, dislodging any stuck objects) may allow you to save the life of someone who is choking.

From the pharynx, air is inhaled into the **larynx** (voice box) and then into the **trachea** (windpipe). The trachea forks into two **bronchi** (singular, *bronchus*), one leading to each lung. Within the lungs, each bronchus branches repeatedly into finer and finer tubes called **bronchioles**. The system of branching tubes looks like an inverted tree, with the trachea as the trunk and the bronchioles as the smallest branches. Bronchitis is an illness in which these small tubes become inflamed.

The bronchioles dead-end in grapelike clusters of air sacs called **alveoli** (singular, *alveolus*) **(Figure 23.19b)**. Each of your lungs contains millions of these tiny sacs. The inner surface of each alveolus is lined with a layer of epithelial cells, where the exchange of gases actually takes place. O_2 enters the bloodstream by diffusing from the air into a web of blood capillaries that surrounds each alveolus. CO_2 diffuses from the blood in the capillaries into the alveoli. The CO_2 in the alveoli is then exhaled through the bronchioles to the bronchus, up through the trachea, and out of the body. The tiny alveoli are delicate and easily damaged, and after age 20 they are not replaced. Destruction of alveoli (usually by smoking, but also by involuntary exposure to air pollution) causes the lung disease emphysema.

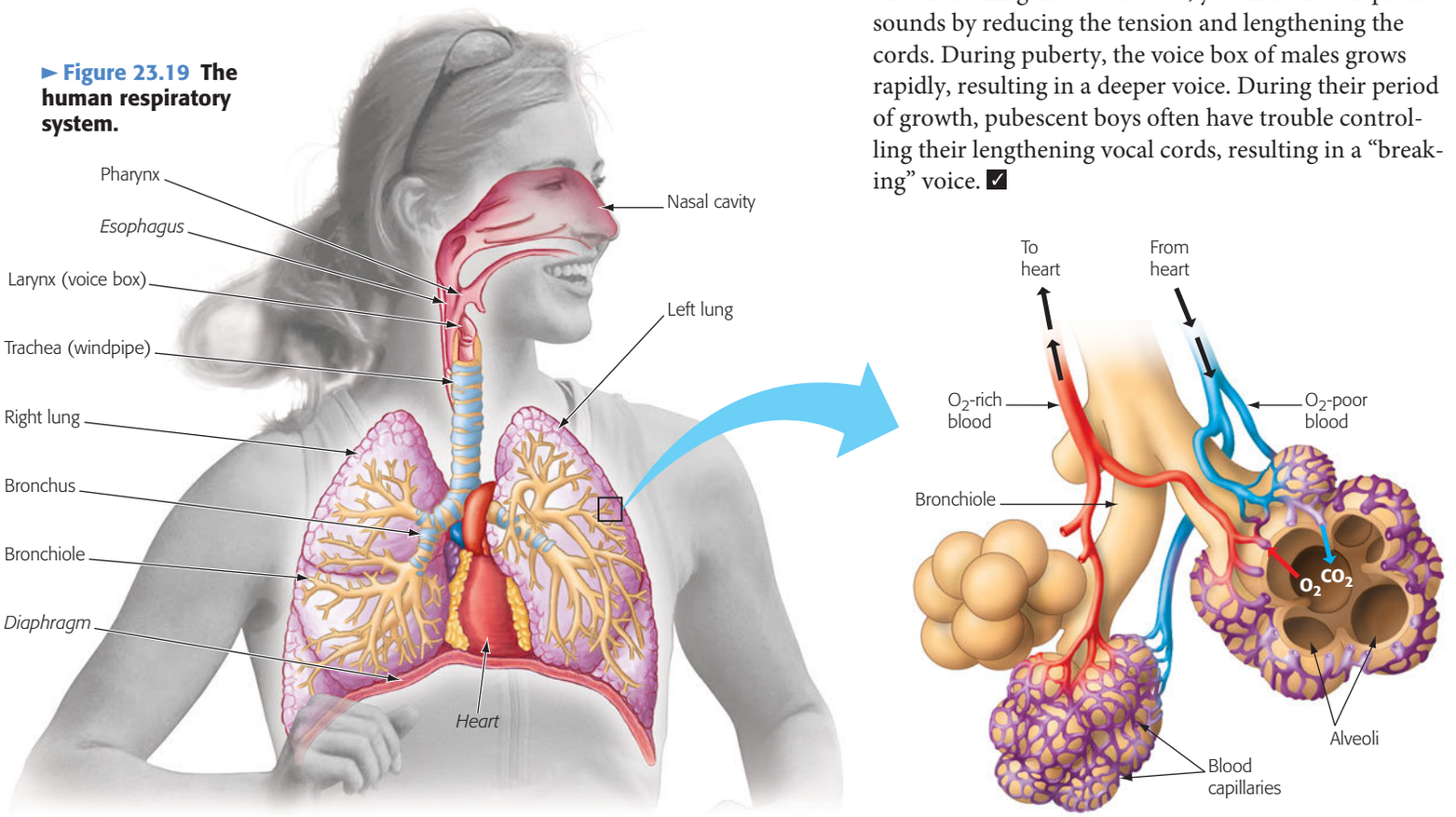
During exhalation, outgoing air moves over a pair of **vocal cords** within the larynx. You produce vocal sounds by flexing muscles in the voice box as air rushes by, stretching the vocal cords and making them vibrate. You make high-pitched sounds by tensing the muscles and shortening the vocal cords; you make lower-pitched sounds by reducing the tension and lengthening the cords. During puberty, the voice box of males grows rapidly, resulting in a deeper voice. During their period of growth, pubescent boys often have trouble controlling their lengthening vocal cords, resulting in a "breaking" voice. ☑

☑ CHECKPOINT

Put the following parts of the human respiratory system in the order that an inhaled breath would encounter them: bronchi, larynx, nasal cavity, alveoli, pharynx, bronchioles, trachea.

Answer: nasal cavity → pharynx → larynx → trachea → bronchi → bronchioles → alveoli

► Figure 23.19 The human respiratory system.



(a) Overview of the human respiratory system

(b) The structure of alveoli. Capillaries surround air sacs called alveoli. These are the sites of gas exchange in the lungs.

Taking a Breath

Figure 23.20 shows the changes that occur during breathing, the alternate inhaling and exhaling of air. If you place your hands on your rib cage and inhale, you can feel your ribs move upward and spread out as muscles between them contract. Meanwhile, your diaphragm moves downward, expanding the chest cavity. All of this increases the volume of the lungs, dropping the air pressure in the lungs to below the air pressure of the atmosphere. The result is that air rushes in through the mouth and nostrils from an area of higher pressure to an area of lower pressure, filling the lungs. Although it may seem that you actively suck in air when you inhale, air actually moves into your lungs passively after the air pressure in them drops. This type of ventilation is called **negative pressure breathing**. (In contrast, amphibians use muscles in the mouth and throat to push air into their lungs, a process called positive pressure breathing.)

During exhalation, the rib and diaphragm muscles relax, decreasing the volume of the chest cavity. This decreased volume increases the air pressure inside the lungs, forcing air to rush out of the respiratory system. Movement of the diaphragm is vital to normal breathing. That is why a punch to the diaphragm can "knock the wind out of you." It shocks the diaphragm muscle, prevents movement of the chest cavity, and stops you from taking a normal breath. Other times, sudden involuntary contractions of the diaphragm force air through the voice box, causing hiccups.

You can consciously speed up or slow down your breathing. You can even hold your breath (although, despite the claims of angry children, you would pass out and return to normal breathing before you turned blue). Usually, however, you aren't aware of breathing; you certainly aren't aware of it when you're asleep. What, then, controls your breathing?

Why does a blow to the midsection knock the wind out of you?

Most of the time, nerves from breathing control centers in the brainstem send signals that maintain a respiratory rate of 10–14 inhalations per minute. This rate can vary, however. **Figure 23.21** highlights one respiratory control system. 1 Levels of CO_2 in the blood affect breathing rate. When you exercise, for example, cellular respiration kicks into high gear, producing more ATP for your muscles and raising the amount of CO_2 in the blood. 2 When the brain senses the higher CO_2 level, 3 breathing control centers increase the breathing rate and depth. As a result, more CO_2 is eliminated in the exhaled air and more O_2 is provided to muscles.

You can become dizzy by hyperventilating—taking excessively rapid, deep breaths. This rapid breathing purges the blood of so much CO_2 that the control centers temporarily slow the signals being sent the diaphragm and rib muscles. Changes in blood chemistry cause arterioles in the brain to constrict, decreasing the brain's blood supply and causing dizziness. Slow breathing continues until the CO_2 level increases enough to switch the breathing control centers back to their normal function. ☑

Figure 23.21 Control centers in the brain that regulate breathing.

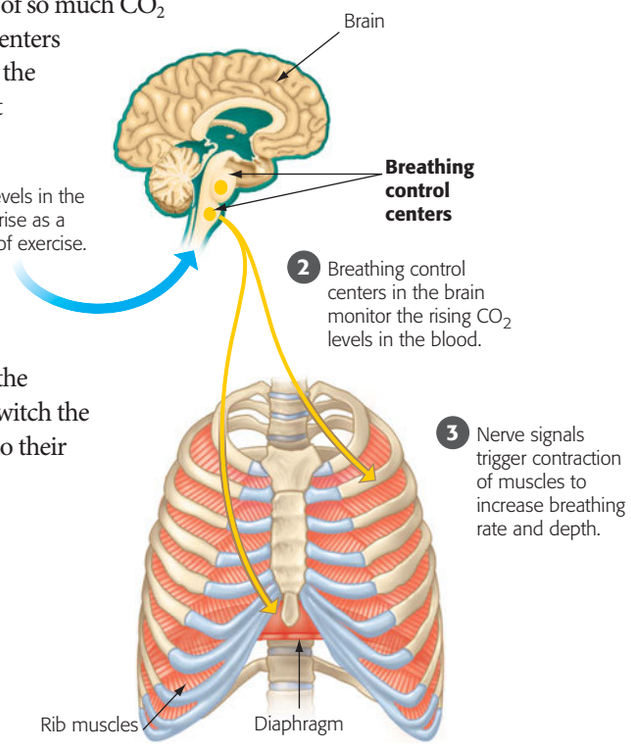
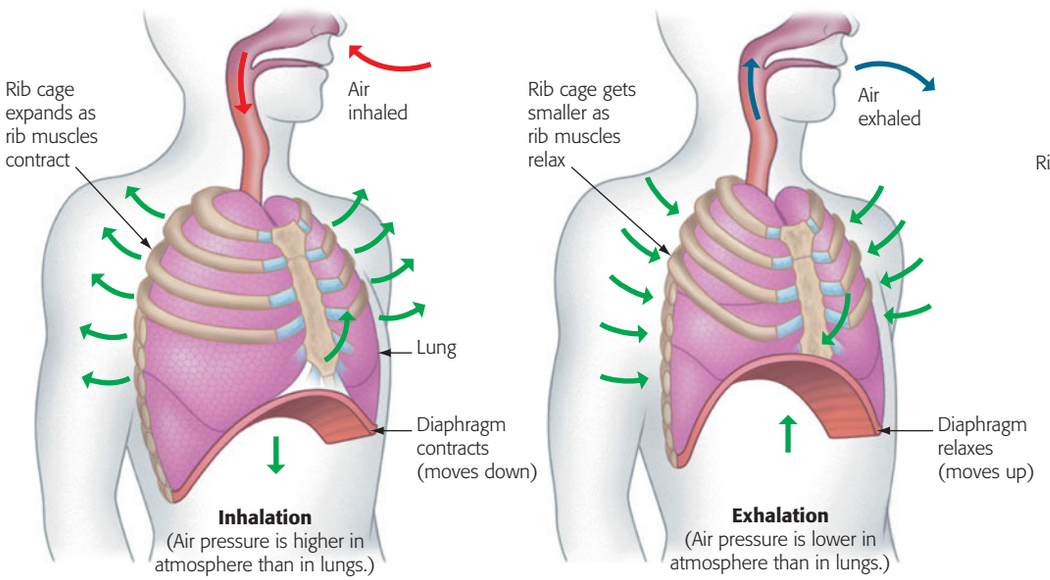


Figure 23.20 How a human breathes.



☑ CHECKPOINT

Why should a hyperventilating person breathe into a paper bag?

Answer: Breathing into a paper bag causes the person to inhale CO_2 back into their lungs. This helps increase the level of CO_2 in the blood, allowing the breathing control centers to function normally.

The Role of Hemoglobin in Gas Transport

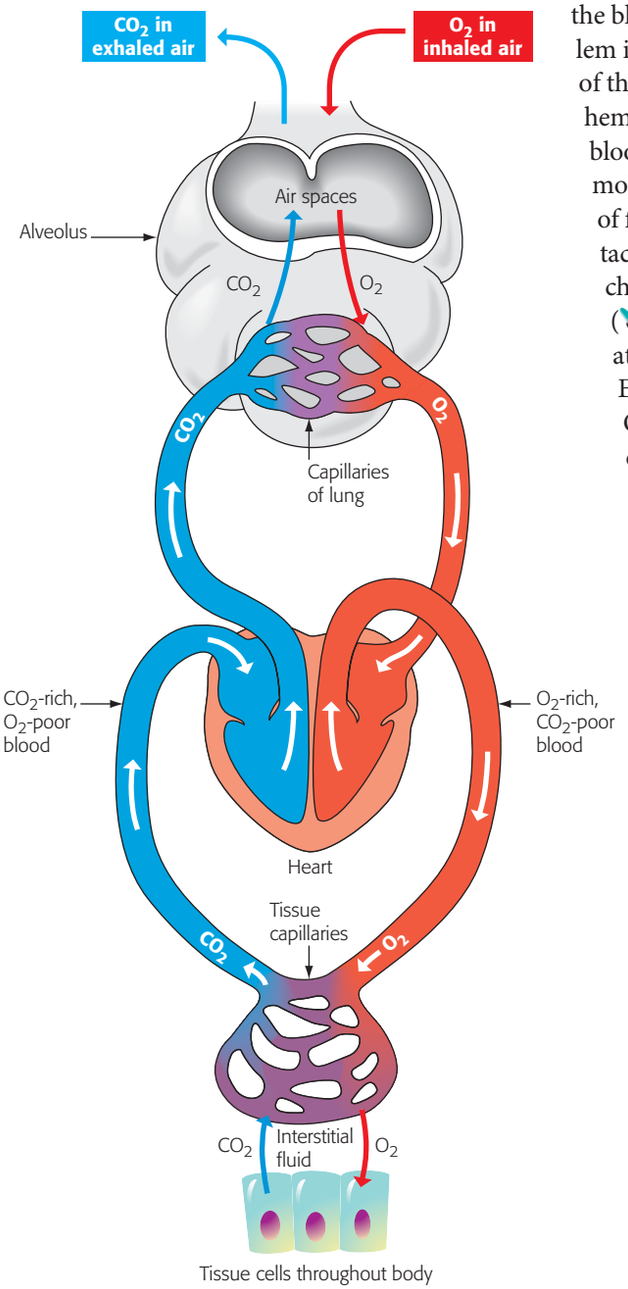
The human respiratory system takes O_2 into the body and expels CO_2, but it relies on the circulatory system to shuttle these gases between the lungs and the body's cells (Figure 23.22). In the lungs, O_2 diffuses from air spaces inside the alveoli into capillaries surrounding the alveoli. Oxygen moves out of the air and into the blood because air is richer in O_2. At the same time, CO_2 diffuses along its own gradient, from the blood out to the air in the lungs.

But there is a problem with this simple scheme: Oxygen does not readily dissolve in blood, so oxygen will not tend to move from the air into the blood on its own. This problem is solved by the fact that most of the O_2 in blood is carried by hemoglobin molecules within red blood cells (Figure 23.23). Each molecule of hemoglobin consists of four polypeptide chains. Attached to each polypeptide is a chemical group called a heme (), at the center of which is an atom of iron (shown in black). Each iron atom can hold one O_2 molecule, so one molecule of hemoglobin can carry a maximum of four molecules of O_2. Each red blood cell has about 250 million molecules of hemoglobin, so one tiny cell can carry 1 billion O_2 molecules. Hemoglobin loads up on oxygen in the lungs, carries it to the body's cells, and unloads it. When hemoglobin binds oxygen, it changes the color of blood to a bright cherry red. Oxygen-poor blood is a dark maroon that appears blue through the skin. This is why a person who has stopped breathing—such as a drowning victim—turns blue.

Because iron (one atom per heme group) is so important in the structure of hemoglobin, a shortage of iron causes less hemoglobin to be produced by the body. In fact, iron deficiency is the most common cause of anemia (a condition in which the blood is deficient in red blood cells). Women are more likely to develop iron deficiency than men because of blood lost during menstruation. Pregnant women can benefit from iron supplements to support the developing fetus.

Besides binding O_2, hemoglobin can bind carbon monoxide (CO), a colorless, odorless gas. In fact, CO binds to hemoglobin even more tightly than O_2 does. Breathing CO can therefore interfere with the delivery of O_2 to body cells. Because CO also interferes with cellular respiration, it can cause rapid death. Sitting in an idling car in an enclosed space, like a garage, can be fatal because CO is emitted as an air pollutant in the exhaust from gasoline-powered engines. And despite its potentially deadly effects, millions of Americans willingly inhale CO in the form of cigarette smoke.

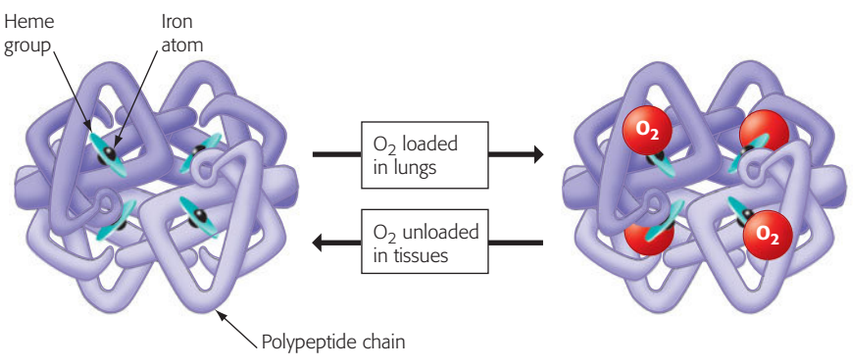
Figure 23.22 Gas transport and exchange in the body. O_2-rich blood is sent from the lungs to capillaries in other body tissues via the heart. O_2 enters body tissue cells and CO_2 leaves, entering the blood. The O_2-poor blood is circulated back to the heart, then to the lungs.



How Smoking Affects the Lungs

Every breath you take exposes your respiratory tissues to potentially damaging chemicals. One of the worst sources of air pollution is tobacco smoke. The visible smoke from burning tobacco is mostly microscopic particles of carbon. Sticking to the carbon particles are more than 4,000 different chemicals, many of which are known to be toxic and even potentially deadly.

Figure 23.23 Hemoglobin loading and unloading O_2. It is the protein hemoglobin within red blood cells that actually binds and transports oxygen molecules.



The epithelial tissue lining our respiratory system is extremely delicate. Its main protection is the mucus covering the cells and the beating hairlike cilia that sweep dirt particles and microorganisms off their surfaces (see Figure 4.22c). Tobacco smoke damages the cells that line the bronchi and trachea, destroying their cilia. This interferes with the normal cleansing mechanism of the respiratory system, allowing more toxin-laden smoke particles to reach and damage the lungs' delicate alveoli. Frequent coughing—common in heavy smokers—is the respiratory system's attempt to replace the action of the dead cilia.

The health statistics associated with smoking are staggering. Every year, smoking kills about 440,000 Americans, more than all the deaths caused by accidents, alcohol and drug abuse, HIV, and murders *combined*. One in two American smokers will die from their habit. On average, adults who smoke cigarettes die 13 to 14 years earlier than nonsmokers. Smokers account for 90% of all cases of lung cancer, one of the deadliest forms of cancer: Only 15% of people diagnosed with lung cancer survive five years, and lung cancer kills more Americans than any other form of cancer by a wide margin. **Figure 23.24a** shows a cutaway view of a pair of healthy human lungs (and heart). In contrast, **Figure 23.24b** shows the lungs of a smoker, turned black from the long-term buildup of smoke particles.

There is no lifestyle choice that can have a more positive impact on your long-term health (and the health of the people you live with) than not smoking. After quitting, it takes about 15 years for a former smoker's risk to even out with that of a nonsmoker, so not starting is clearly the best option. Unfortunately, even nonsmokers may be affected by tobacco, as studies have found that secondhand cigarette smoke is also a substantial health hazard, particularly to young children. ☑

▼Figure 23.24 Healthy versus cancerous lungs.



(a) Healthy lung (nonsmoker) **(b) Cancerous lung (smoker)**

☑ CHECKPOINT

How does smoking damage the lungs?

Answer: Smoking damages the epithelial tissue that lines the respiratory system, preventing pollutants from being removed. These pollutants can then damage the delicate alveoli of the lungs where gas exchange occurs.



Athletic Endurance EVOLUTION CONNECTION

Evolving Endurance

In this chapter, we've used the topic of athletic endurance to illustrate the importance of the circulatory and respiratory systems. We've seen how conditioning and even cheating can be used to boost athletic performance by improving the ability of these systems to deliver oxygen to muscles. But as it turns out, not everyone needs conditioning to boost their stamina: Some people are born that way.

Tibet, a plateau region of Asia within the Himalayan mountain range, is the highest region on Earth, with an average elevation of 16,000 feet—nearly 3 miles high! Many Tibetans live and work at altitudes above 13,000 feet, where the amount of oxygen that reaches the blood is 40% less than at sea level **(Figure 23.25)**. Without extensive conditioning, such altitudes render most people sick or even unconscious. Many Tibetans work as mountain guides yet rarely experience "mountain sickness." How have the Tibetan people come to be so tolerant of their surroundings?



▲Figure 23.25 A Tibetan mountaineer. Tibetans are renowned for their ability to live and work at high altitudes.

A 2010 study by a team of Chinese biologists demonstrated that over the last several thousand years, Tibetans have evolved the ability to thrive at high altitude. By comparing the genomes of 50 Tibetans with the genomes of 40 nearby low-dwelling Chinese, the researchers found at least 30 genes that differed between the two populations. In each case, one version of the gene that is rare among the low-dwelling Chinese group had evolved to become common among Tibetans. Many of these genes are ones already known to contribute to the functioning of the circulatory and respiratory systems. Furthermore, the scientists conducting this study were able to identify the mechanism of natural selection: At high altitude, people who lack such gene mutations have three times the infant mortality rate of people who harbor the mutations. Thus, there is a clear survival and reproductive advantage for those Tibetans who inherit the mutant genes. The Tibetan ability to work and thrive atop the Himalayans can be understood as both a testament to their inborn endurance and another manifestation of biology's unifying theme of evolution.

Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Unifying Concepts of Animal Circulation

The circulatory system facilitates the exchange of materials and energy between the cells of an organism and its environment.

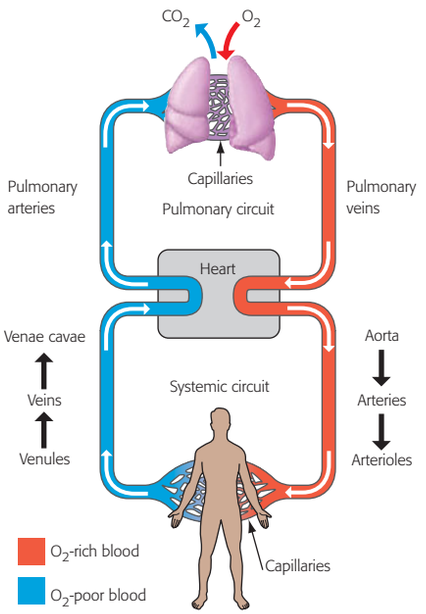
Open and Closed Circulatory Systems

In an open circulatory system, circulating fluid is pumped through open-ended tubes and circulates freely among cells. In a closed circulatory system, the circulating fluid (blood) is confined within tubes.

The Human Cardiovascular System

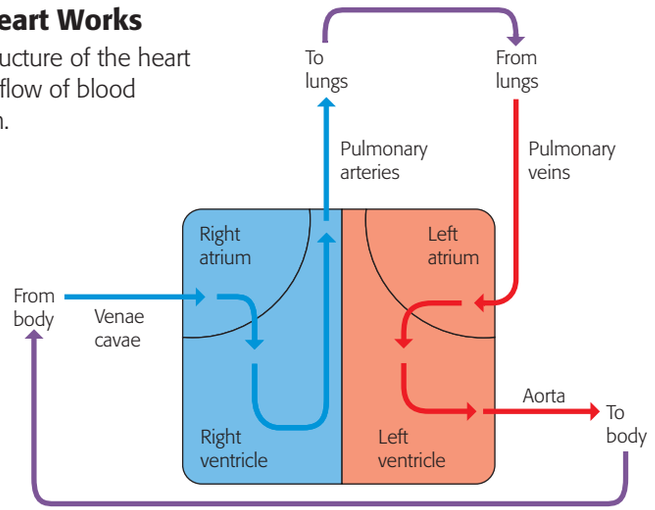
The Path of Blood

Trace the path of blood in this figure, noting where blood is oxygen-poor and where it is oxygen-rich.



How the Heart Works

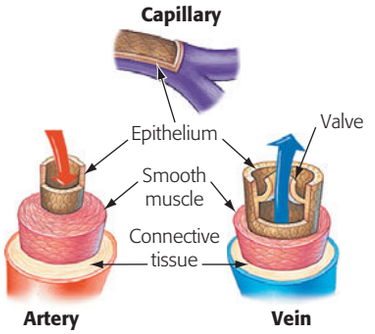
Review the structure of the heart by tracing the flow of blood in this diagram.



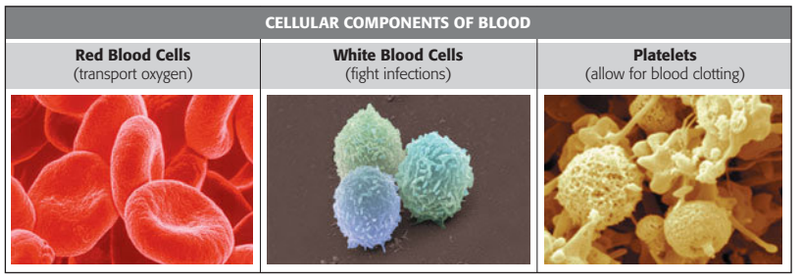
The cardiac cycle is composed of two phases: systole (contraction) and diastole (relaxation). The pacemaker, which sets the tempo of the heartbeat, generates electrical impulses that stimulate the atria and ventricles to contract.

Blood Vessels

Muscular arteries carry blood away from the heart. Exchange between the blood and interstitial fluid occurs across the thin walls of capillaries. Valves in the veins and contractions of surrounding skeletal muscle keep blood moving back to the heart.



Blood



New blood cells are continually formed from stem cells found in red bone marrow.

Cardiovascular Disease

Diseases of the heart and blood vessels—including heart attack and stroke—kill more Americans than any other type of disease. Atherosclerosis is the buildup of fatty substances in the inner walls of arteries.

Unifying Concepts of Animal Respiration

The respiratory system facilitates gas exchange.

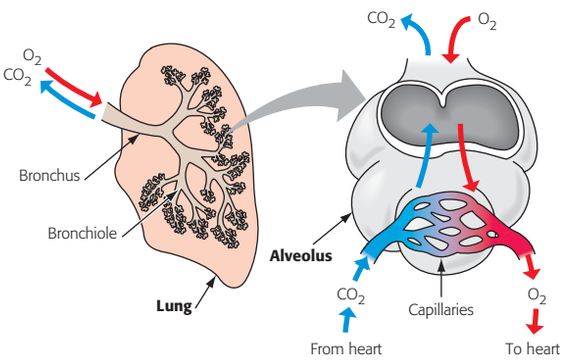
The Structure and Function of Respiratory Surfaces

Various respiratory surfaces have evolved in animals. The respiratory surface is the part of the body where gas exchange takes place. This can include the entire body surface, gills, tracheae, or lungs.

The Human Respiratory System

The Structure and Function of the Human Respiratory System

When you take a breath, air moves sequentially from the



nostrils and/or mouth to the pharynx, larynx, trachea, bronchi (which enter the lungs), bronchioles, and finally the alveoli (the actual respiratory surfaces).

Taking a Breath

During inhalation, the chest cavity expands and air pressure in the lungs decreases, causing air to rush into the lungs. During exhalation, air pressure in the lungs increases and air moves out of the lungs. Breathing rate is set by breathing control centers in the brain, which in turn are influenced by CO_2 concentrations in the blood.

The Role of Hemoglobin in Gas Transport

After O_2 enters the lungs, it binds to hemoglobin in red blood cells and is transported to body tissue cells by the circulatory system.

How Smoking Affects the Lungs

Tobacco smoke damages the respiratory surfaces of the lungs, impairing alveolar function and causing multiple health problems.

SELF-QUIZ

1. What is the difference between an open circulatory system and a closed circulatory system?
2. Why is the following statement false? "All arteries carry oxygen-rich blood, while all veins carry oxygen-poor blood."
3. Match each chamber of the heart with its function.

a. left atrium	1. receives blood from the body via the venae cavae
b. right atrium	2. sends blood to the lungs via the pulmonary arteries
c. left ventricle	3. receives blood from the lungs via the pulmonary veins
d. right ventricle	4. sends blood to the body via the aorta

4. Some babies are born with a small hole in the wall of muscle that separates the left and right ventricles. How does this affect the oxygen content of the blood pumped out of the heart in the systemic circuit?
5. People who do not get enough iron in their diet run the risk of developing _____.
6. Match each element of the blood with its main function.

a. plasma	1. transporting O_2
b. platelets	2. fighting infections
c. red blood cells	3. carrying dissolved elements
d. white blood cells	4. aiding in clotting

7. A heart-healthy diet can significantly reduce your risk of cardiovascular disease. Name three foods that should be eaten in abundance for a heart-healthy diet, and name three dietary components that should be limited.
8. What is the main difference between the respiratory organs of fishes and humans in terms of where they are located in the body?
9. The respiratory surface of vertebrate lungs consists of tiny sacs within the lungs called _____.
10. During inhalation, when the diaphragm contracts and the ribs spread apart, air pressure inside the lungs
    a. increases.
    b. decreases.
    c. decreases, then increases.
    d. is unchanged.
11. Why is carbon monoxide deadly?
    a. It binds to hemoglobin in white blood cells in place of O_2.
    b. It binds to hemoglobin in red blood cells in place of O_2.
    c. It binds to hemoglobin in red blood cells in place of CO_2.
    d. It binds to hemoglobin in white blood cells in place of CO_2.

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

12. Mammals have a four-chambered heart, with two ventricles and two atria. So do birds, alligators, and crocodiles, but other living reptiles have a three-chambered heart, with just one ventricle. Paleontologists debate whether dinosaurs had a three-chambered or a four-chambered heart. Long-necked sauropod dinosaurs could have had unusual circulatory demands because their head may have been raised far above the heart. The farther the head is above the heart, the greater the systolic pressure needs to be for blood to reach the brain. For example, the long-necked dinosaur *Brachiosaurus* may have carried its head as much as 6 m (20 feet) above its heart. It is estimated that such an anatomy demanded a systolic blood pressure of 500 mm of mercury for blood to reach the brain! Some paleontologists consider this evidence that dinosaurs had a four-chambered heart that supported a dual circulatory system similar to that of birds and mammals, rather than the three-chambered heart of most nonbird reptiles. Can you explain why?
13. During a college swim meet, John told his friends that before a race he likes to "charge up" on oxygen by hyperventilating so he can hold his breath longer. Although John is correct that this will allow him to hold his breath longer, it is not for the reason that he gave. How is he mistaken? Why is this use of hyperventilation actually very dangerous?

BIOLOGY AND SOCIETY

14. Several years ago, a 19-year-old woman received a bone marrow transplant from her 1-year-old sister. The woman was suffering from a form of leukemia and was almost certain to die without a transplant. The woman's parents decided to have another child in a final attempt to provide their daughter with a matching donor. Although the ethics of the parents' decision were criticized, doctors reported that this situation is not uncommon. In your opinion, is it acceptable to have a child to provide tissue or an organ? Why or why not?
15. Many endurance sports—such as the Tour de France bicycle race—have been wracked by blood doping scandals in recent years. Should all forms of artificial red blood cell boosting be banned? What punishment do you think is appropriate for an athlete caught cheating in this way? Should athletes have the right to train however they please, even if it involves artificial therapies?

24 The Body's Defenses



Fighting a killer. Activists in South Africa march in support of AIDS research.



CHAPTER CONTENTS

Innate Defenses 518
Adaptive Defenses 521
Immune Disorders 528

CHAPTER THREAD
HIV and AIDS

BIOLOGY AND SOCIETY
The Elusive Search for an AIDS Vaccine 517
THE PROCESS OF SCIENCE
How Was HIV First Linked to AIDS? 523
EVOLUTION CONNECTION
HIV Evolution 530



HIV and AIDS BIOLOGY AND SOCIETY

The Elusive Search for an AIDS Vaccine

One of the greatest medical advances of the 1900s was the development of vaccines against deadly viral diseases. A vaccine contains a harmless version or piece of a disease-causing microbe. Once it has been injected, the vaccine can prime the body's defenses so they are ready to mount a vigorous attack if the actual virus is ever encountered. Because there are few antiviral drugs, vaccines are the only medical weapons that can be deployed against many harmful viruses.

One important target of vaccine research is HIV, the human immunodeficiency virus, which causes AIDS (acquired immunodeficiency syndrome). HIV is deadly because it destroys the defenses of its host, leaving the body unable to fight most invaders. In other words, HIV's treacherous means of action wipes out the very body defenses that would normally offer protection.

Despite decades of effort by the world's scientists, an effective AIDS vaccine has never been found. This is not for lack of trying. In an early trial, participants were injected with a virus that infects pet birds, modified to carry three HIV genes. This trial was halted when data showed that the vaccine offered no benefit in helping to prevent infection by the real AIDS virus. Another set of trials used a vaccine made from a modified form of a protein found on the surface of HIV. These studies were also unsuccessful. Researchers were quite surprised, then, by the results of a recent AIDS vaccine study that followed 16,000 volunteers from Thailand over six years. This trial used the two vaccines that had previously been shown to fail. But for reasons no one understands, the *combination* of both of these vaccines offered some protection. Although the difference between the control and experimental groups was so small as to be barely measurable, these results offered the first hint of success after 20 years of effort. When it comes to understanding how to vaccinate against AIDS, we appear to be no closer today than we were decades ago.

AIDS kills by disabling the body's defenses. And vaccines work by stimulating those same defenses. The ongoing battle with HIV is just one illustration of how important your built-in system of defenses is to maintaining your health. This chapter examines how these defenses work to protect your body. We'll also look at how knowledge of this system has been applied to improve human health, what happens when the body's protective system malfunctions, and the continuing struggle against AIDS.

Innate Defenses

Nearly everything in the environment—including most of what you touch or taste and even the air you breathe—teems with microbes, some of which can make you sick. Yet you do not constantly become ill, thanks to your **immune system**, your body's system of defenses against infectious disease.

The human body has three cooperative lines of defense that protect you against the constant barrage of **pathogens**, disease-causing viruses and microorganisms (Figure 24.1). The first line of defense is external—barriers that prevent pathogens from getting deep inside the body. If that line fails, some internal protections stand ready as a second line of defense. These first two lines of defense are **innate defenses**—that is, they are always deployed and at the ready. Later in the chapter, we'll discuss the third line of defense, the **adaptive defenses** (also known as acquired defenses), which are internal defenses that must be activated by exposure to specific invaders. While nearly all animals have innate defenses, only vertebrates have adaptive defenses. Throughout this chapter, we'll focus on the innate and adaptive defenses of humans.

☑ CHECKPOINT

What makes the body's first two lines of defense "innate"?

Answer: These defenses are at full strength before an invader is ever encountered.

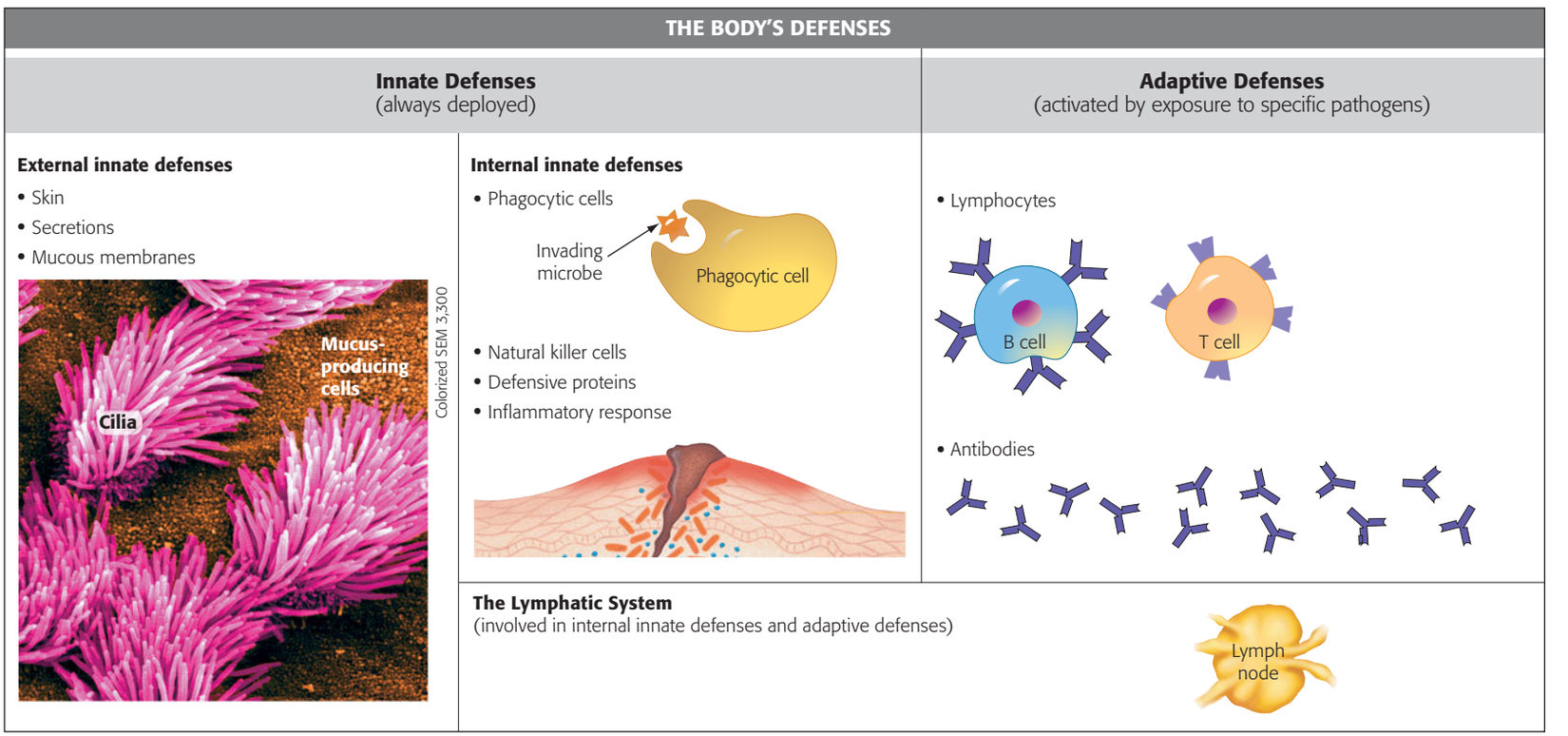
External Innate Defenses

For a foreign substance to get inside the body, it must first get by the body's external barriers. These barriers form an important protective front line because they *prevent* infection, as opposed to the body's other defenses, which act only *after* infection has occurred.

Some barriers block or filter out microbes. Intact skin forms a tough outer layer that most bacteria and viruses cannot penetrate. Nostril hairs filter many particles from the incoming air. Wax in the ear canal traps particles before they can get deep inside. Organ systems that are open to the external environment (such as the respiratory and reproductive systems) are lined with mucous membranes that secrete mucus, a sticky fluid that traps bacteria, dust, and other particles. Beating cilia extending from cells of the respiratory tract sweep mucus with the trapped particles outward until it is swallowed or expelled by sneezing, coughing, or blowing the nose.

External barriers also include chemical defenses in the form of antimicrobial secretions. Sweat, saliva, and tears contain enzymes that disrupt bacterial cell walls. Glands produce oils and acids that make the skin inhospitable to many microbes. Concentrated stomach acid kills most of the bacteria we swallow before they can enter the bloodstream. ☑

▼ Figure 24.1 Overview of the body's defenses. Note that the lymphatic system is involved in both innate and adaptive defenses.



Internal Innate Defenses

When an invader breaches the body's external barriers, it is no longer an outsider. To fight pathogens within the body, the animal's immune system must first detect foreign particles and cells. In other words, an immune system must be able to distinguish nonself from self. This is accomplished by a second line of innate defenses that consists of white blood cells and defensive proteins **(Figure 24.2)**.

Two types of white blood cells contribute to your internal innate defenses: phagocytic cells and natural killer cells. **Phagocytic cells** engulf foreign cells or molecules and debris from dead cells by phagocytosis, or "cellular eating" (see Figure 5.18). **Natural killer (NK) cells** can often recognize virus-infected or cancerous body cells. When contact is made, the NK cells release chemicals that kill the diseased cells.

The defensive proteins that aid in internal innate defense include **interferons**, which are produced by body cells that have been infected by viruses **(Figure 24.3)**. Virus-infected cells 1 make and release interferons that 2 bind to plasma membrane receptors on nearby uninfected cells. This binding stimulates the healthy cells to 3 produce proteins that inhibit viral reproduction. Because of their strong antiviral properties, injected interferons are sometimes used to treat some viral diseases, such as hepatitis and genital warts. **Complement proteins** attack pathogens directly. Some coat the surfaces of microbes, making them easier for phagocytic cells to engulf. Others cut lethal holes in microbial membranes, causing the invading cells to burst (lyse). Still other proteins help trigger the inflammatory response, our next topic. ☑

☑ CHECKPOINT

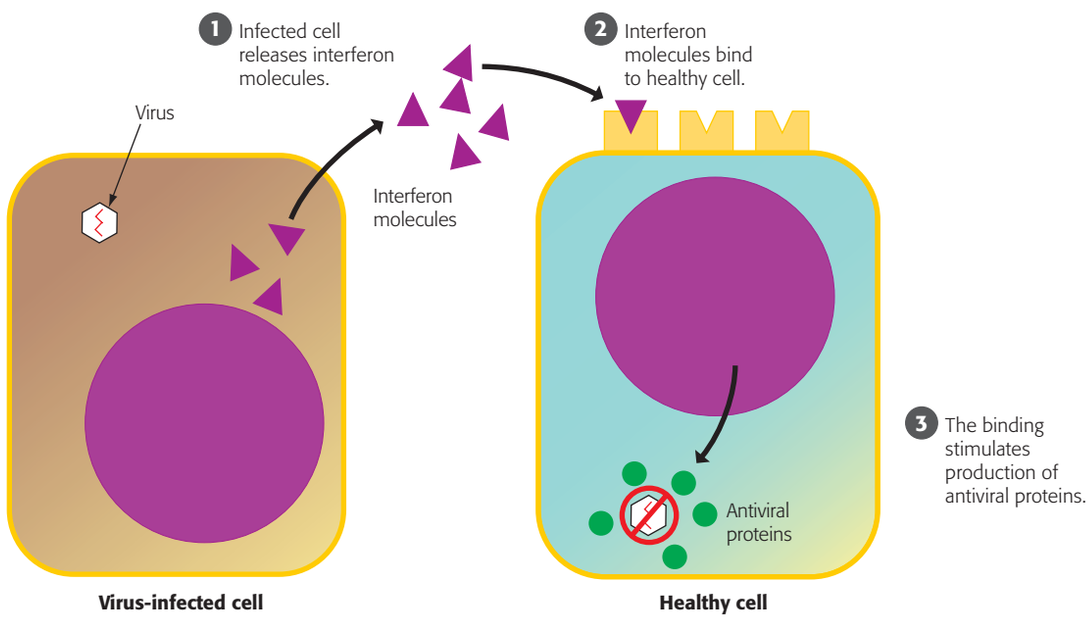
What are the two main components of your body's internal innate defenses?

Answer: white blood cells and proteins

▼ **Figure 24.2 The body's second line of defense.** When the external barriers fail, a set of internal innate defenses stands ready as the body's next line of protection.

INTERNAL INNATE DEFENSES			
White Blood Cells		**Defensive Proteins**	
Phagocytic cells (engulf foreign cells or substances)	**Natural killer cells** (destroy infected and cancerous body cells)	**Interferons** (protect body cells against viral infection)	**Complement proteins** (cause invading microbial cells to lyse)

► **Figure 24.3 The action of interferon.** When a virus infects a body cell, the cell produces and releases interferon molecules that bind to receptors on healthy cells, stimulating them to produce antiviral proteins that inhibit the growth of other viruses.



The Inflammatory Response

What happens if you get a splinter in your finger and don't take care of it? The next day, the finger is often red, swollen, painful, and warm to the touch. These are signs of the **inflammatory response** to injury and infection, another example of an internal innate defense in action **(Figure 24.4)**. When tissue becomes damaged (from cuts, scratches, bug bites, or burns, for example), ❶ the injured cells release chemicals that trigger various innate defenses. One such chemical signal, **histamine**, ❷ causes nearby blood vessels to dilate (widen) and leak fluid into the wounded tissue, causing it to swell. The swelling helps the tissue to heal by diluting toxins, bringing extra oxygen, and delivering platelets and clotting proteins that promote scabbing. The chemical signals also attract phagocytic cells. ❸ These cells engulf bacteria and the remains of body cells killed by bacteria or by the physical injury. The pus that often fills an infected injury consists of phagocytic cells, fluid that leaked from capillaries, and other tissue debris.

Why does pus form around a healing cut?

Damaged cells also release chemical signals that increase blood flow to the damaged area, causing the wound to turn red and warm. (The word *inflammation* means "setting on fire.") In response to severe tissue damage or infection, damaged cells may release other chemicals that travel through the bloodstream to the brain, where they stimulate a fever that may discourage bacterial growth.

Anti-inflammatory drugs such as aspirin and ibuprofen dampen the normal inflammatory response and help reduce swelling and fever. Aspirin, for example, inhibits dilation of blood vessels, which reduces swelling. This is an example of treating the symptoms of an illness (for example, swelling) without addressing the underlying cause (which is the injury or infection).

All the defenses you've learned about so far are called innate because they're ready "off the rack"; that is, innate defenses are already deployed in the body and at the ready without any preparation. Soon you'll learn about the body's adaptive defenses—ones that are "custom-tailored" to specific invaders. But first let's look at a system that contributes to both innate and adaptive defenses: the lymphatic system. ☑

☑ CHECKPOINT

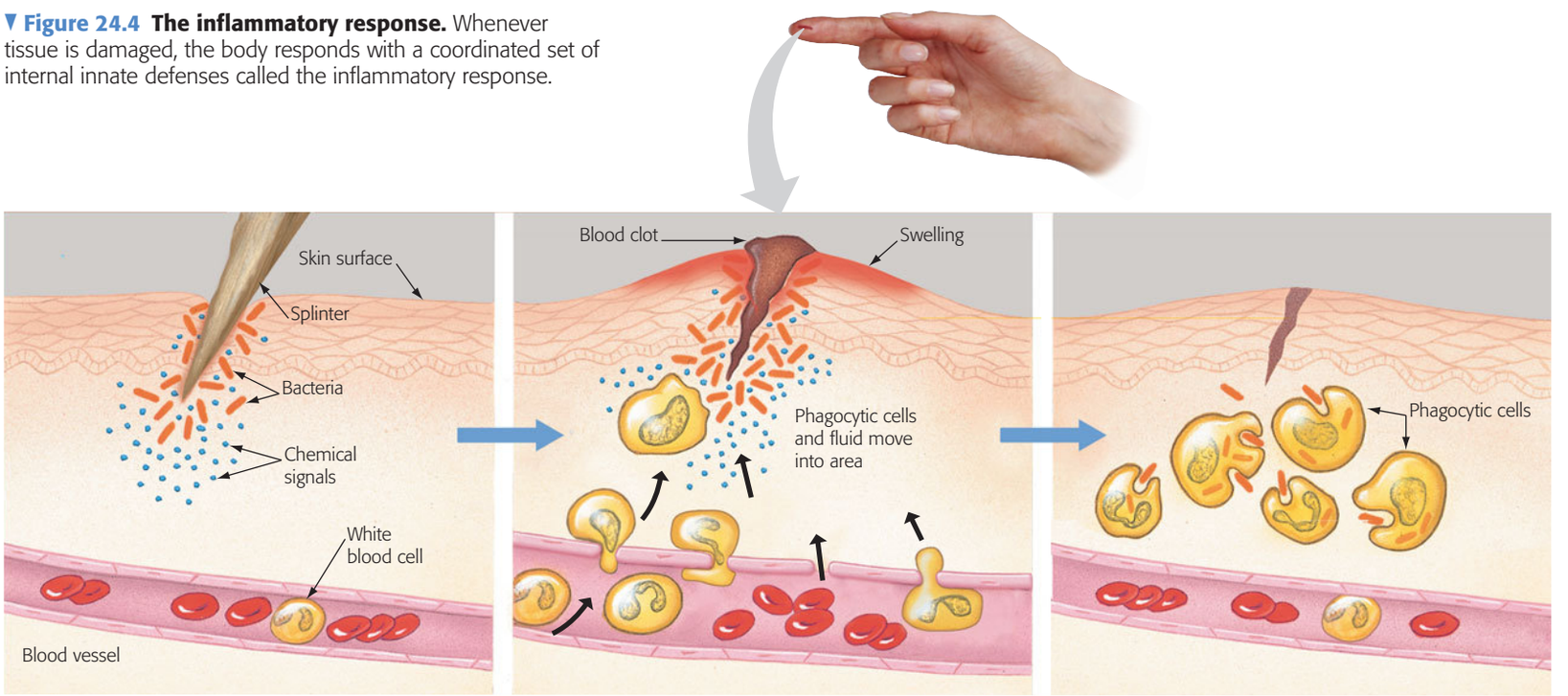
Name the signs of the inflammatory response.

Answer: swelling, redness, warmth, pain, and sometimes fever

The Lymphatic System

The **lymphatic system** consists of a branching network of vessels, numerous **lymph nodes** (little round organs packed with white blood cells), and several other organs **(Figure 24.5)**. The lymphatic vessels carry fluid called **lymph**, which is similar to the interstitial fluid surrounding body cells. The two main functions of the lymphatic system are to return tissue fluid to the circulatory system and to fight infection.

▼ Figure 24.4 The inflammatory response. Whenever tissue is damaged, the body responds with a coordinated set of internal innate defenses called the inflammatory response.



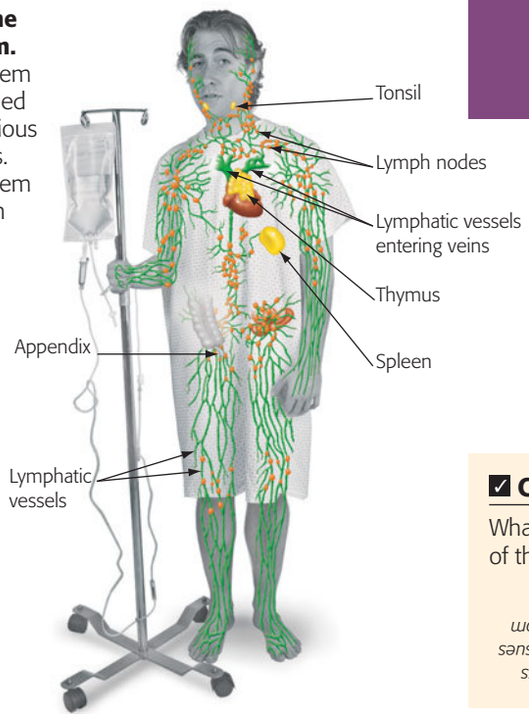
❶ Tissue injury; release of chemical signals such as histamine

❷ Dilation and increased leakiness of local blood vessels; migration of phagocytic cells to the area

❸ Phagocytic cells engulf bacteria and cell debris; tissue heals

A small amount of the fluid that enters the tissue spaces from the blood in a capillary bed does not reenter the blood capillaries. Instead, it flows into lymphatic capillaries that are intermingled with blood capillaries. Now called lymph, this fluid drains from the lymphatic capillaries into larger and larger lymphatic vessels. Eventually, the fluid reenters the circulatory system through two large lymphatic vessels that fuse with veins near the shoulders.

When your body is fighting an infection, the lymphatic system is the main battleground. Lymph nodes fill with huge numbers of white blood cells, causing the tender "swollen glands" in your neck and armpits that your doctor feels for as a likely sign of infection. Because lymphatic vessels penetrate nearly every tissue, lymph can pick up microbes from infection sites just about anywhere in the body and deliver them to the lymphatic nodes and other organs. As the lymph passes through the lymphatic tissue, phagocytic cells engulf invaders. Lymph also carries white blood cells involved in the adaptive defenses, which we'll discuss next. ☑



► **Figure 24.5 The lymphatic system.** The lymphatic system transports fluid called lymph through various vessels and organs. The lymphatic system plays a role in both the innate and adaptive defenses.

☑ CHECKPOINT

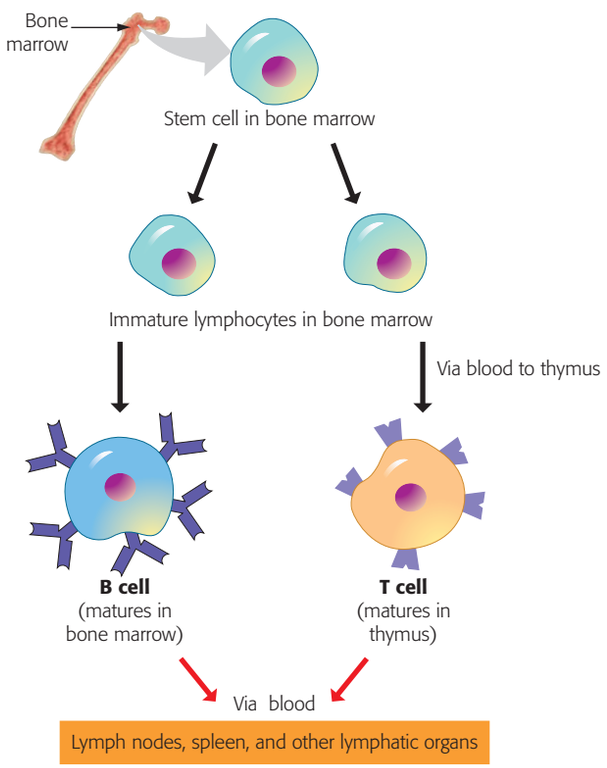
What are the two functions of the lymphatic system?

Answer: to collect fluid that leaks from blood capillaries within tissues and to help protect the body from foreign cells and molecules

Adaptive Defenses

When the innate defenses fail to ward off a pathogen, the adaptive defenses provide a third line of defense (see Figure 24.1). This third line is called *adaptive* because it is activated only after exposure to specific pathogens. Adaptive defenses depend on white blood cells called **lymphocytes** that recognize and respond to specific invading pathogens. There are two types of lymphocytes: B cells and T cells. Like all blood cells, lymphocytes originate from stem cells in the bone marrow **(Figure 24.6)**. Some immature lymphocytes continue developing in the bone marrow; these become specialized as **B cells**. Other immature lymphocytes migrate via the blood to the thymus, a gland in the chest, where they become specialized as **T cells**. Both B cells and T cells eventually make their way to the lymph nodes and other lymphatic organs. Over 2 trillion lymphocytes are spread throughout the bloodstream and lymphatic system, making possible an elaborately coordinated response to infection.

Whereas the innate defenses are always ready to fight a variety of infections, lymphocytes must be primed by exposure to a foreign molecule. Any molecule that elicits a response from a lymphocyte is called an **antigen**. Most antigens are molecules on the surfaces of viruses or foreign cells, such as cells of bacteria or parasitic worms. Antigens can also be molecules from mold spores, pollen, and house dust, as well as molecules on cell surfaces of transplanted tissue. We'll look at how lymphocytes recognize antigens and then explore how they respond to these invaders. ☑



◄ **Figure 24.6 The development of lymphocytes.** All lymphocytes arise in the bone marrow, but they mature in different locations: B cells in the bone marrow and T cells in the thymus. Once mature, lymphocytes are released into the blood and lymphatic system.

☑ CHECKPOINT

1. What are the two main types of lymphocytes?
2. What is an antigen? Name some examples.

Answers: 1. B cells and T cells 2. An antigen is a molecule that elicits a response from a lymphocyte. Examples include pollen, dust, and proteins on the surfaces of microorganisms.

Recognizing the Invaders

When a B cell develops in bone marrow or a T cell develops in the thymus, the cell synthesizes molecules of a specific protein and builds them into its plasma membrane. These protein molecules (purple in Figure 24.6) are antigen receptors that stick out from the cell's surface. All the antigen receptors on a particular lymphocyte can bind to only one specific type of antigen. Once these receptors are in place, a B cell or T cell can recognize a single specific type of antigen and mount an immune response against it. One cell may recognize an antigen on the mumps virus, for instance, while another detects an antigen on a tetanus-causing bacterium.

The immune system develops a great diversity of B cells and T cells—enough to recognize and bind to just about every possible antigen. A small population of each kind of lymphocyte lies in wait in your body, ready to recognize and respond to a specific antigen. Only a tiny fraction of the lymphocytes will ever be used, but they are all available if needed. It is as if the immune system maintains a huge standing army of soldiers, each made to recognize one particular kind of invader. The majority of soldiers never encounter their target and remain idle. But when an invader does appear, chances are good that some lymphocytes will recognize it, bind to it, and call in reinforcements.

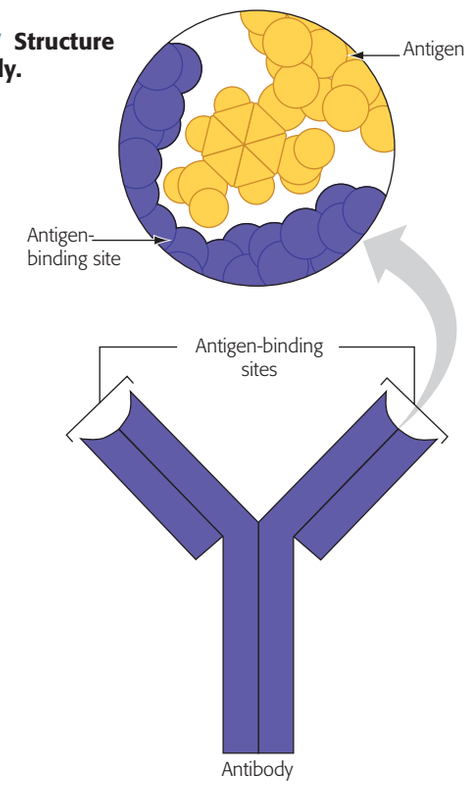
After binding to an antigen, a B cell can give rise to short-lived cells that secrete receptor-like molecules that circulate in the blood and lymph. Such a secreted molecule is called an **antibody** and is specific for that same antigen **(Figure 24.7)**. Each antibody molecule consists of four polypeptide chains joined together to form a Y shape. The tip of each arm of an antibody forms an antigen-binding site, a region responsible for recognizing and binding to the antigen. An antigen-binding site and the antigen it binds have complementary shapes, like an enzyme and substrate or a lock and key. A huge variety in the shapes of the binding sites of different antibodies enables the immune system to react to any kind of antigen. The main role of an antibody is to mark an antigen by combining with it to form an antigen-antibody complex. As you'll see later, such binding triggers responses that help destroy the invader.

Because of their ability to tag specific molecules or cells, antibodies are widely used in laboratory research, in clinical diagnosis, and in the treatment of disease. Using cell cultures, researchers can artificially produce large quantities of antibodies, which have many uses. Some are used to treat disorders of the immune system, such as transplant rejection and autoimmune diseases, particularly rheumatoid arthritis. Herceptin, a genetically engineered antibody, is used to treat certain cases of aggressive breast cancer. A common type of home pregnancy test uses antibodies to detect a hormone called human chorionic gonadotropin (HCG), present in the urine of pregnant women. When a testing strip is dipped into urine, antibodies on the strip bind to any HCG that is present, causing the strip to change color. And antibodies are one of the keys to diagnosing HIV infection, as you'll see next. ✓

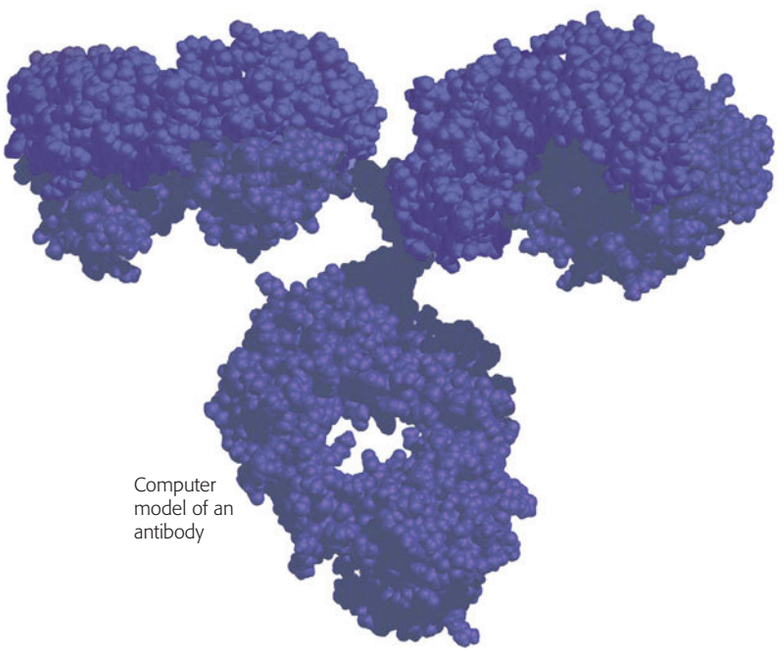
✓ CHECKPOINT

What are antibodies? What is their role in the adaptive immune response?

Answer: receptor proteins secreted by short-lived B cells; to mark an antigen by binding to it



► **Figure 24.7 Structure of an antibody.**





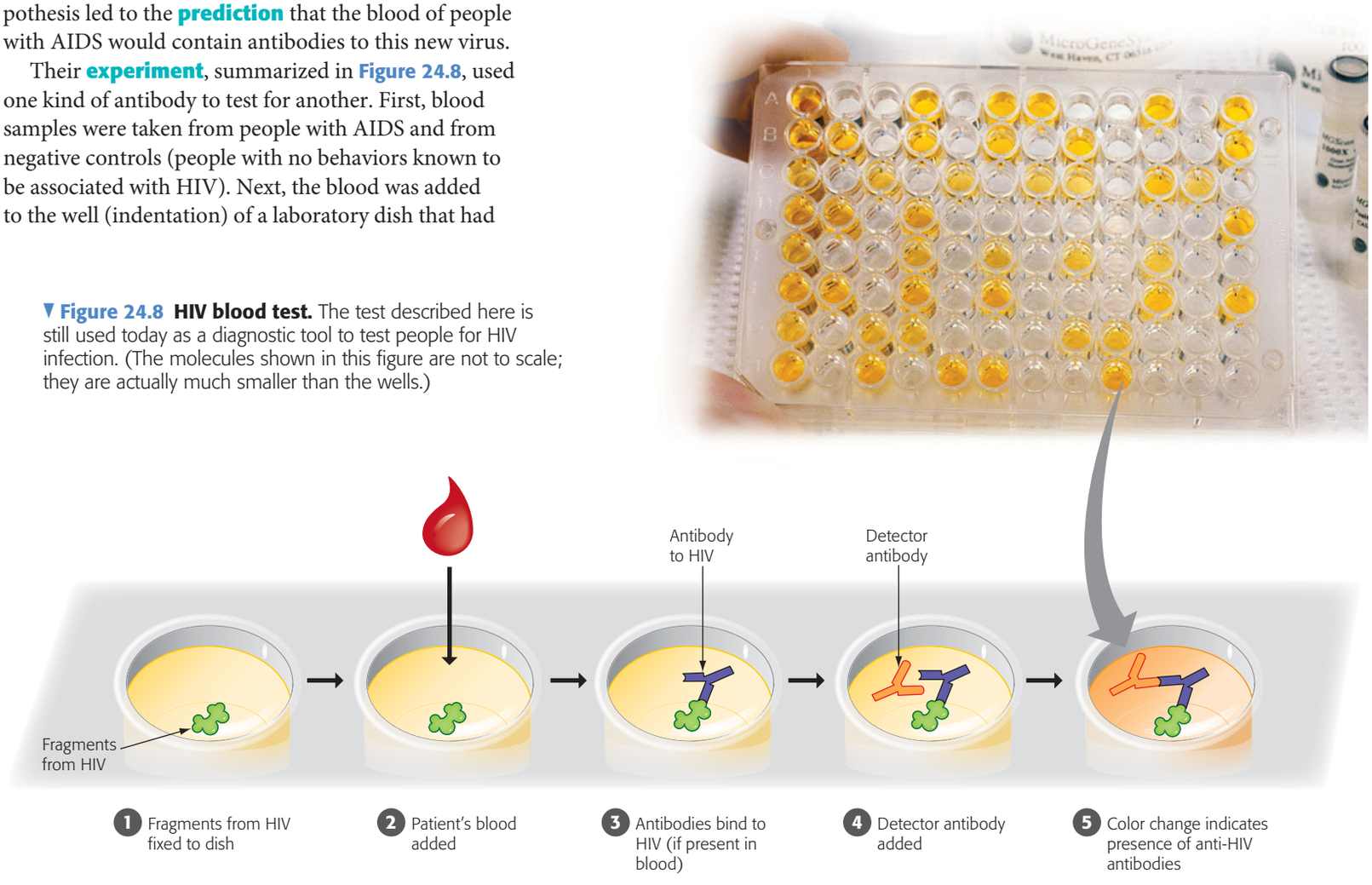
HIV and AIDS THE PROCESS OF SCIENCE

How Was HIV First Linked to AIDS?

The disease now called AIDS was first recognized by doctors in 1981. **Observation** of the spread of AIDS among sexual partners, intravenous drug users, and blood transplant recipients strongly suggested that some infectious agent caused the disease (rather than, say, an environmental poison). But the key **question**—What pathogen causes AIDS?—remained unanswered for three years after AIDS was first described.

In 1984, a group of researchers led by Robert Gallo, of the U.S. National Cancer Institute, announced a major breakthrough. Their work began with the **hypothesis** that AIDS was caused by a new virus discovered by French biologist Luc Montagnier (who received a 2008 Nobel Prize for his discovery). This hypothesis led to the **prediction** that the blood of people with AIDS would contain antibodies to this new virus.

Their **experiment**, summarized in Figure 24.8, used one kind of antibody to test for another. First, blood samples were taken from people with AIDS and from negative controls (people with no behaviors known to be associated with HIV). Next, the blood was added to the well (indentation) of a laboratory dish that had 1 fragments from the suspected virus stuck to the bottom. 2 If the test subject's blood had antibodies to the virus, they would 3 bind to the virus, forming an antibody-virus complex that was fixed to the dish. 4 Finally, another kind of antibody, one that binds to any human antibody, was added along with an enzyme that 5 would react with the complex to produce a color. The dishes were washed, so any remaining color could only indicate antibodies that had bound to the virus (which was attached to the dish so it wouldn't wash away). Their **results** showed that almost every patient with AIDS had antibodies to the new virus, whereas none of the control people did. In a series of classic papers published in 1984, Gallo combined these results with other evidence to prove that the new virus, now called HIV, causes AIDS.



▼ **Figure 24.8 HIV blood test.** The test described here is still used today as a diagnostic tool to test people for HIV infection. (The molecules shown in this figure are not to scale; they are actually much smaller than the wells.)

Responding to the Invaders

Now that you know how lymphocytes recognize antigens, we'll look at how they fight these intruders. B cells and T cells have distinct responses, but they carry out a coordinated attack along with the innate defenses.

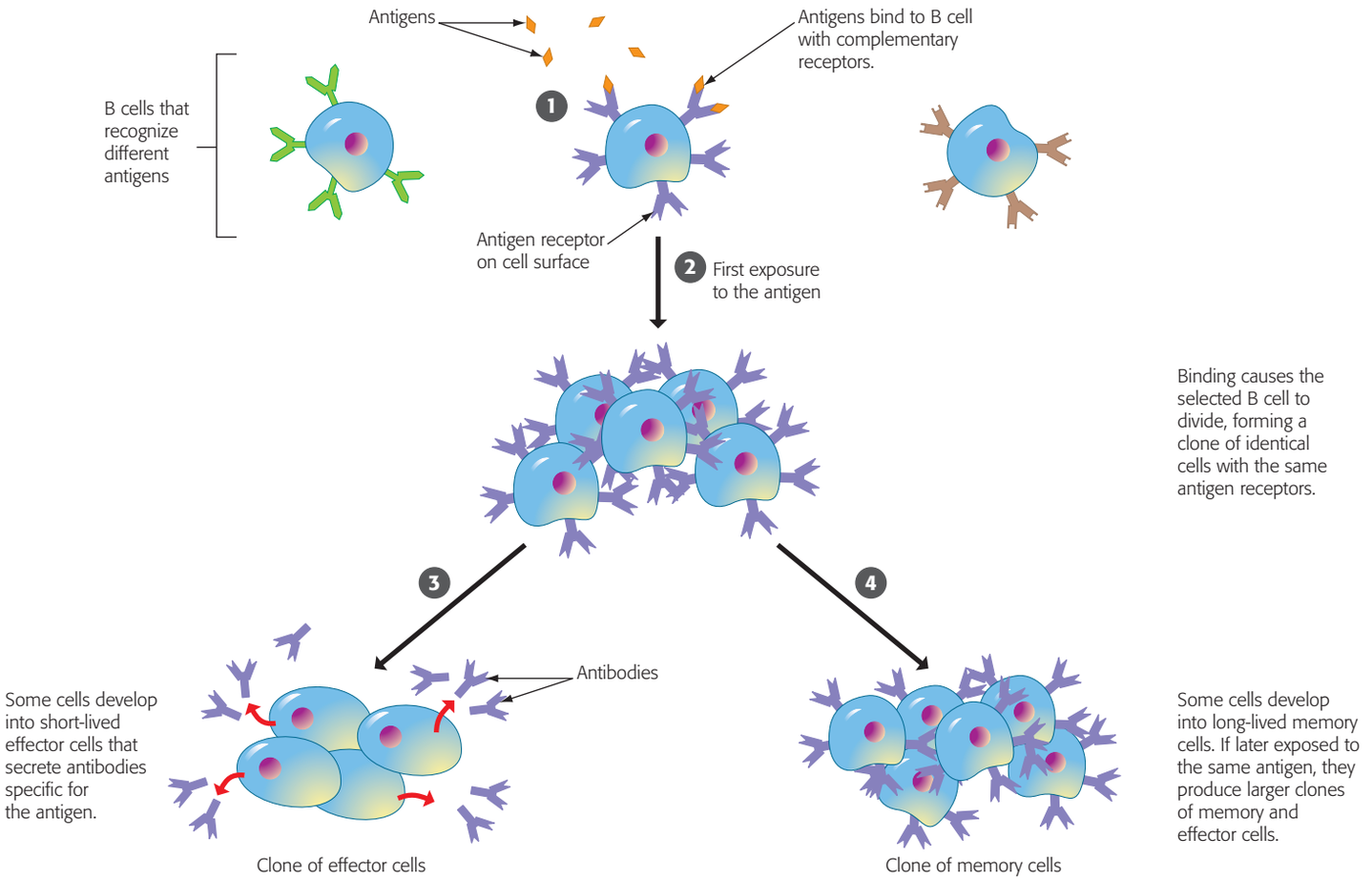
Clonal Selection: Multiplying Lymphocytes

Recall that the immune system maintains a vast collection of different kinds of white blood cells. With so many kinds of B cells and T cells, how does the body marshal enough of the right kind of lymphocyte to fight a specific invading antigen? The key is a process called **clonal selection**. The concept is simple. At first, an antigen activates only a tiny number of lymphocytes with receptors specific to that antigen. These "selected" cells then proliferate, forming a clone of cells (a population of genetically identical B cells or T cells) that are specific for the stimulating antigen.

Figure 24.9 illustrates how clonal selection of lymphocytes works, using B cells as an example; a similar mechanism activates clonal selection for T cells. The top row shows three different B cells, each with its own specific type of antigen receptor embedded in its surface. 1 Once an antigen enters the body, it binds with a B cell that has complementary receptors. Other lymphocytes without the appropriate binding sites are not affected. 2 The binding activates the cell—it grows, divides, and develops further. This produces clones of cells specialized for defending against the very antigen that triggered the response. 3 Some of the newly produced cells are short-lived cells that have an immediate effect against the antigen and are therefore called **effector cells**. In the case of B cells, the effector cells secrete huge quantities of antibodies into the blood and lymph—as many as 2,000 copies per second. These antibodies bind to the invading antigen and, as you'll see later, contribute to its destruction or block its harmful effects.

The first response to exposure of lymphocytes to an antigen, called the **primary immune response**, takes several days to produce effector cells via clonal selection. The antibodies produced by effector B cells reach their peak levels about two weeks after first exposure and then start to decline. Each effector cell lives only four or five days, and the primary immune response subsides as the effector cells die out. 4 Clonal selection also produces memory cells, which we'll discuss next.

Figure 24.9 Clonal selection. In this example of clonal selection, an antigen "selects" a B cell that binds to it and causes the cell's proliferation. A similar kind of clonal selection operates on T cells.



Immunological Memory

Figure 24.9 shows that clonal selection produces both effector cells and memory cells. **Memory cells** are long-lived cells that respond to subsequent exposures to the antigen by giving rise to effector cells and more memory cells. Thus, clonal selection produces not only cells that will fight the first exposure to an antigen (effector cells) but also cells that will respond to future exposures (memory cells).

What's in all those shots that you were given as a young child?

In contrast to short-lived effector cells, memory cells can last decades in the lymph nodes, poised to be activated by a second exposure to the antigen. When the antigen is encountered again, the memory cells that bind to it initiate a faster and stronger response called the **secondary immune response**. The activated memory cells multiply quickly, producing a large new clone of lymphocytes. In the case of B cells, the new clone produces antibodies that are often more effective than those produced during the primary immune response.

Thus, with adaptive defenses, unlike innate defenses, exposure to a particular foreign molecule enhances future responses to that same molecule. For example, if a person gets chicken pox or receives the chicken pox vaccine, memory cells are formed that have receptors against molecules on the virus that causes this disease. If the virus enters the body again, the memory cells react quickly, giving rise to effector cells that usually destroy the virus before symptoms appear. One early observation of the effect of the immune system's remarkable "memory" is in the writings of the Greek historian Thucydides, almost 2,400 years ago. He noted that survivors of the plague could safely care for people who were sick or dying of that disease, "for the same man was never attacked twice—never at least fatally."

Vaccination

Immunity is obtained after an infection, but it can also be achieved artificially by **vaccination** (also called immunization). As discussed in the Biology and Society section, the immune system can be confronted with a **vaccine** composed of a harmless version of a disease-causing microbe or one of its parts. The vaccine stimulates the immune system to mount defenses against these harmless antigens. These defenses will also be effective against the actual pathogen because it has similar antigens. When a person has been successfully vaccinated, the immune system responds quickly if exposed to the pathogen. Such protection may last for life.

In the United States, most children receive a series of shots starting soon after birth **(Figure 24.10)**. The shots include vaccinations against diphtheria/pertussis/tetanus (DPT, or "diptet"), polio, hepatitis, chicken pox, and measles/mumps/rubella (MMR). In the United States, widespread childhood vaccination has virtually eliminated several of these diseases, including polio and mumps. As noted in the Biology and Society section, researchers are trying to develop an HIV vaccine, although success remains elusive (for reasons to be discussed in the Evolution Connection section). One of the major triumphs of modern vaccination involves smallpox, a potentially fatal viral infection that affected over 50 million people a year worldwide in the 1950s. A massive vaccination effort has been so effective that in 1977 the World Health Organization of the United Nations declared smallpox to be completely eradicated. Since 2001, however, the U.S. government has stockpiled millions of doses of smallpox vaccine and has vaccinated high-risk military and health-care workers in case the smallpox virus is used in a bioterrorist attack.

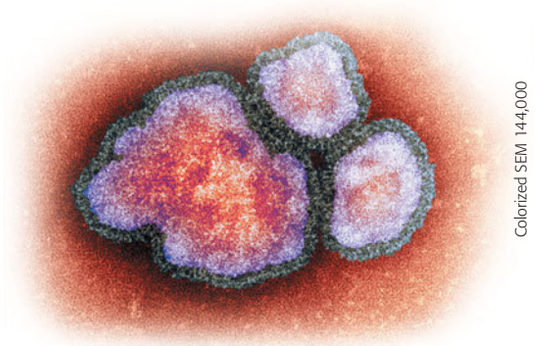
So far, you've seen that the binding of foreign antigens triggers lymphocytes of the immune system to multiply, producing clones of effector cells and memory cells. Next we'll look at how the effector cells disable or destroy the intruders. ☑

☑ CHECKPOINT

Given that there are so many possible pathogens that can invade your body, how does your immune system produce enough of the right cells to fight off a major infection?

Answer: *The process of clonal selection causes those few cells with receptors that are complementary to the antigens of the infectious agent to selectively multiply.*

▼ Figure 24.10 Vaccinating a child against the measles virus (inset).



Colorized SEM 144,000



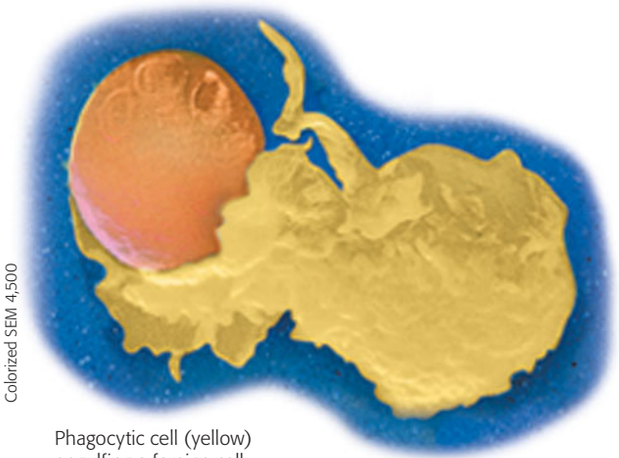
B Cells and the Humoral Immune Response

The secretion of free-floating antibodies into the blood and lymph by B cells is called the **humoral immune response**. (The word *humoral* comes from *humors*, an old term for blood and other body fluids.) This response defends primarily against bacteria and viruses that are circulating in body fluids. Sometimes the binding of antibodies neutralizes antigens by physically blocking them. For example, the attachment of antibodies to viral surface proteins may inhibit the virus from entering body cells. Other times, the binding to viruses or foreign cells causes the formation of clumps of pathogens that are easily captured by circulating phagocytic cells. Additionally, the antigen-antibody complex may activate complement proteins that destroy the antigen-carrying cells.

T Cells and the Cell-Mediated Immune Response

Whereas the humoral immune response involves antibodies secreted by effector B cells into the blood and lymph, effector T cells respond directly to antigens that have already entered body cells. Because this response is carried out directly by cells rather than by antibodies, it is called the **cell-mediated immune response**. It involves two main kinds of T cells: helper T cells and cytotoxic T cells.

Helper T cells bind to other white blood cells that have previously encountered an antigen. In the example in Figure 24.11, 1 a phagocytic cell engulfs a microbe and breaks it into fragments, each of which is a foreign antigen (*nonself* molecule). Protein molecules belonging to the phagocytic cell, which are referred to as *self* proteins because they belong to the body itself, 2 bind to the foreign antigens and 3 display them on the cell's outer surface. 4 Receptors embedded in the helper T cell's plasma membrane recognize and bind to the combination of self protein and nonself molecule displayed on the phagocytic cell.



Colorized SEM 4,500

Phagocytic cell (yellow) engulfing a foreign cell

▼ Figure 24.11 Interaction of a phagocytic cell and a helper T cell.

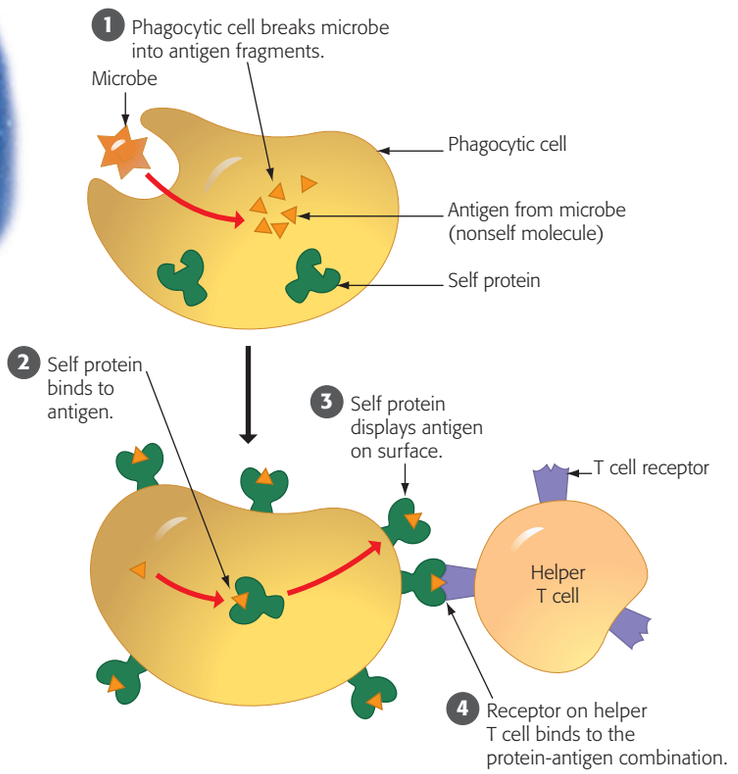
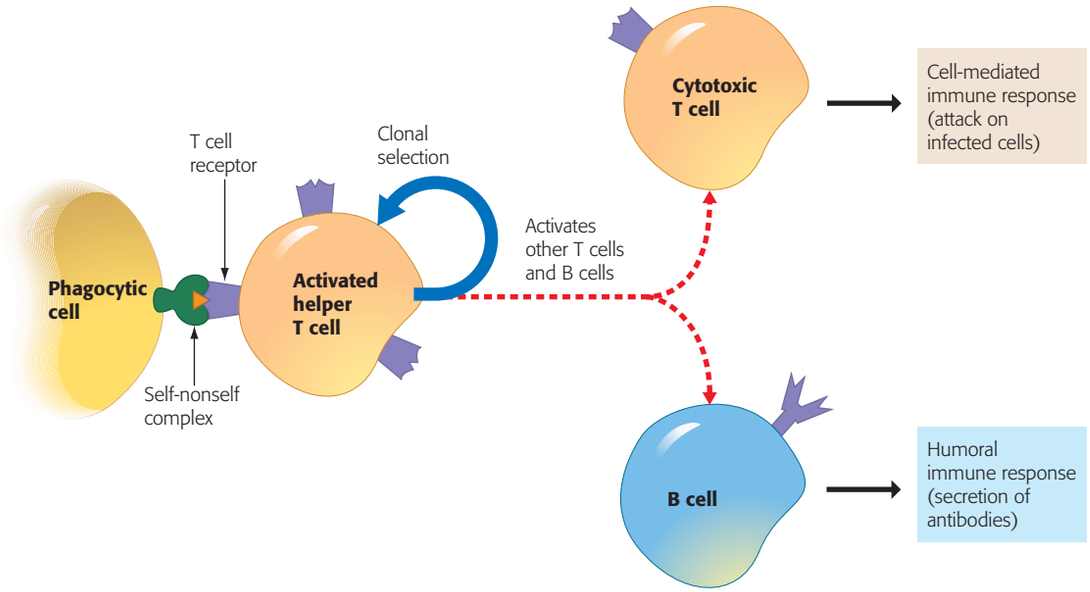


Figure 24.12 The roles of an activated helper T cell. Activated helper T cells promote both the cell-mediated immune response (via cytotoxic T cells) and the humoral immune response (via B cells).



The binding of a T cell receptor to the self-nonself combination activates the helper T cell (Figure 24.12). An activated helper T cell responds in several ways. It grows and divides, producing more activated helper T cells, as well as memory T cells (not shown in figure). In addition, it stimulates the activity of cytotoxic T cells and helps activate B cells, thus engaging the humoral immune response as well. Given its central role in so many aspects of immunity, it is not surprising that an HIV infection—which destroys helper T cells specifically—has such devastating consequences.

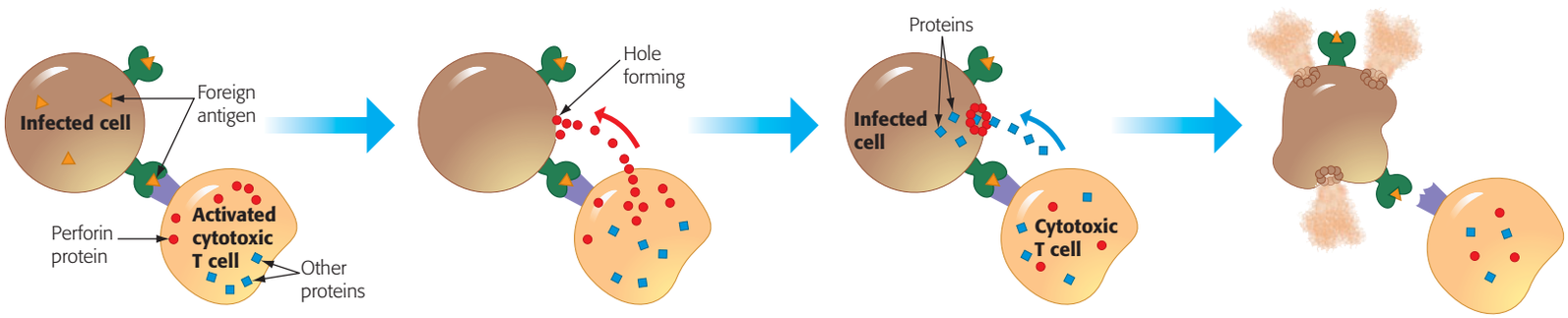
Cytotoxic T cells are the only T cells that actually kill infected cells. They identify infected body cells in the same way that helper T cells identify their targets: through binding of a receptor to a self-nonself complex. As shown in Figure 24.13, (1) a cytotoxic T cell binds to an infected cell. The binding activates the T cell. (2) The activated cell synthesizes and discharges several proteins, including one called perforin that makes holes in the infected cell's plasma membrane. (3) Other T cell proteins enter the infected cell through the newly created hole and trigger a process that results in (4) death of the cell by lysis (bursting). ☑

☑ CHECKPOINT

What are the two main types of effector T cells, and what does each do?

Answer: Helper T cells stimulate other body defenses. Cytotoxic T cells destroy infected cells.

Figure 24.13 How a cytotoxic T cell kills an infected cell.



(1) Cytotoxic T cell binds to infected cell, becoming activated and producing perforin.

(2) Perforin makes holes in infected cell's plasma membrane.

(3) Other proteins enter target cell through holes created by perforin.

(4) Infected cell is destroyed by lysis (bursting).

Immune Disorders

If the intricate interplay of immune cells goes awry, problems can arise that range from mild irritations to deadly diseases. In this section, we'll examine some of the consequences of a malfunctioning immune system.

Allergies

Allergies are exaggerated sensitivities to otherwise harmless antigens in the environment. Antigens that cause allergies are called **allergens**. Common allergens include protein molecules on pollen grains, on the feces of tiny mites that live in house dust, and in animal dander (shed skin cells). Allergic reactions typically occur very rapidly in response to tiny amounts of an allergen.

If someone is allergic to dust, what are they really allergic to?

The symptoms of an allergy result from a two-stage reaction outlined in **Figure 24.14**. The first stage, called sensitization, occurs when a person is first exposed to an allergen—pollen, for example. (1) An allergen enters the bloodstream. There it binds to B cells with complementary receptors, tagging them for clonal selection (as in Figure 24.9). (2) The B cells then proliferate and secrete large amounts of antibodies to that allergen. (3) Some of these antibodies attach to receptor proteins on the surfaces of mast cells, body cells that produce histamine and other chemicals that trigger the inflammatory response.

Allergy symptoms do not arise until the second stage, which begins when the same allergen enters the body and (4) binds to the antibodies on the mast cells. In response to this binding, (5) the mast cells release histamine, which triggers allergy symptoms. Histamine causes blood vessels to dilate and leak fluid, causing nasal irritation, itchy skin, and tears. Because allergens usually enter the body through the nose and throat, symptoms are often most prominent there. Antihistamines are drugs that interfere with histamine's action and give temporary relief from an allergy.

Allergic reactions range from seasonal nuisances to severe, life-threatening responses. Anaphylactic shock is an especially dangerous type of allergic reaction. Some people are extremely sensitive to certain allergens, such as the venom from a bee sting or allergens in peanuts or shellfish. Any contact with these allergens causes a sudden release of inflammatory chemicals. Blood vessels dilate abruptly, causing a rapid and potentially fatal drop in blood pressure, a condition called shock. Fortunately, anaphylactic shock can be counteracted with injections of the hormone epinephrine **(Figure 24.15)**. ☑

☑ CHECKPOINT

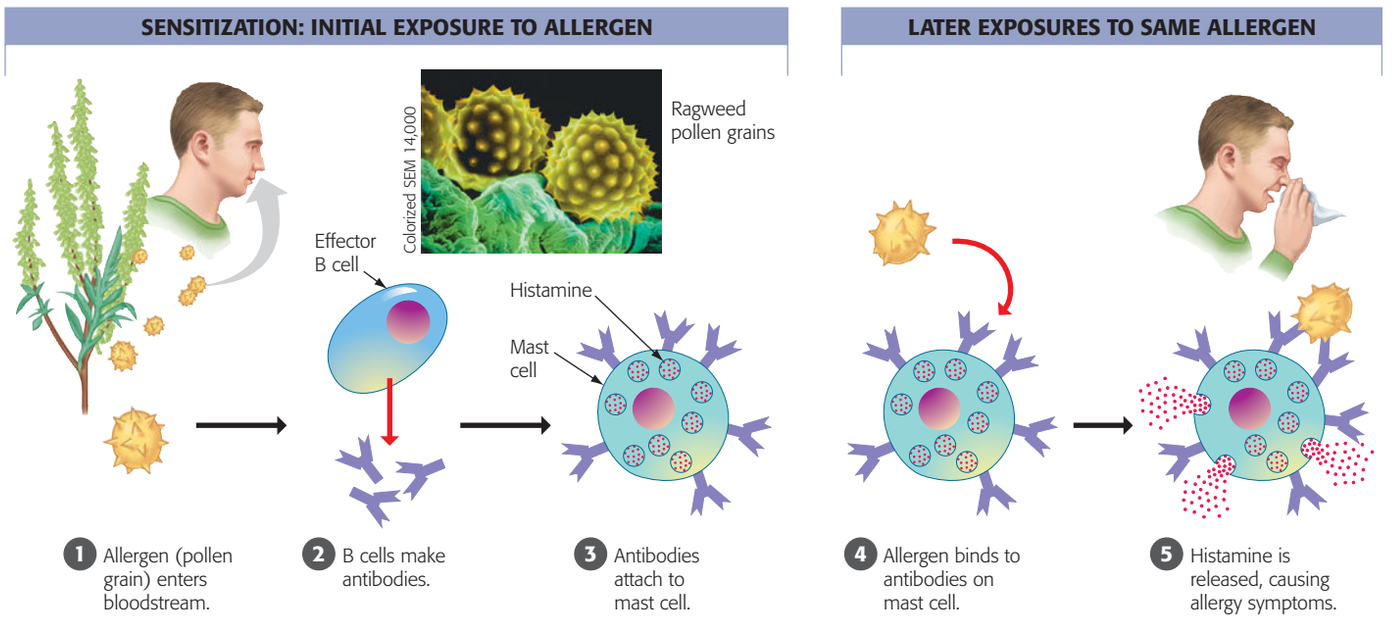
Why does it take at least two exposures to an allergen to trigger an allergic reaction?

Answer: The first time you are exposed to an allergen, it merely sensitizes you by causing the attachment of specific antibodies to mast cells. A second exposure causes the mast cells to release chemicals that trigger the symptoms of an allergic response.

▼ Figure 24.15 Single-use epinephrine syringes. People who know they have severe allergies can carry single-use syringes that contain the hormone epinephrine (also called adrenaline). An injection can quickly stop a life-threatening allergic reaction.



► Figure 24.14 How allergies develop. The first exposure to an allergen causes sensitization. Subsequent exposures to the same allergen produce allergy symptoms.



Autoimmune Diseases

The immune system's ability to distinguish self from nonself enables it to battle foreign invaders without harming healthy body cells. Self proteins on the surfaces of cells are the key to this ability. Each person's cells have a particular collection of self proteins that mark body cells as "off-limits" to attacks from the immune system. Because every person has a unique set of self proteins, the immune system can distinguish the body's cells from those of other people and from microbes.

The immune system's ability to recognize and attack foreign antigens does not always work in our favor. For example, when a person receives an organ transplant, the immune system recognizes the donor's cells as foreign and attacks them. To minimize rejection, doctors look for a donor with self proteins matching the recipient's as closely as possible (often a close relative) and use drugs to suppress the immune response. Such drugs greatly reduce the risk of rejection but increase the risk of infections and must often be administered for life.

Why might someone have to live in a sterile "bubble"?

Autoimmune diseases result when the immune system improperly turns against the body's own molecules. In systemic lupus erythematosus (lupus), B cells make antibodies against many sorts of self molecules, even proteins and DNA released by the normal breakdown of body cells. Rheumatoid arthritis is an autoimmune disease that leads to damage and painful inflammation of the cartilage and bones of joints **(Figure 24.16)**. In type 1 (insulin-dependent) diabetes, the insulin-producing cells of the pancreas are the targets of cytotoxic T cells. In multiple sclerosis (MS), T cells wrongly attack proteins in neurons (see Figure 27.2), often causing progressive muscle paralysis. Recent research suggests that Crohn's disease, a chronic inflammation of the digestive tract, may be caused by an autoimmune reaction against bacteria that normally inhabit the intestinal tract.

Immunodeficiency Diseases

In contrast to autoimmune diseases are a variety of defects called **immunodeficiency diseases**. Immunodeficient people lack one or more of the components of the immune system and are therefore susceptible to infections that would not ordinarily cause a problem. In the rare genetic disease called severe combined immunodeficiency (SCID), both B cells and T cells are absent or inactive. People with SCID are extremely vulnerable to even minor infections, forcing them to live behind protective barriers (providing inspiration for various "bubble boy" stories in the popular media) or to receive bone marrow transplants.

Immunodeficiency is not always an inborn condition; it may be acquired later in life. For instance, Hodgkin's disease, a type of cancer that affects lymphocytes, can depress the immune system. Radiation therapy and drug treatments used against many cancers can have the same effect. Next we will look at the most dreaded acquired immunodeficiency disease of our time: AIDS. ☑

☑ CHECKPOINT

1. What is an autoimmune disease?
2. What is an immunodeficiency disease?

Answers: **1.** a disease in which cells of the immune system attack certain of the body's own cells as foreign **2.** a disease in which one or more parts of the immune system are defective, resulting in an inability to fight infections

▼ Figure 24.16 Rheumatoid arthritis. The hands in this photo and X-ray are from a person with rheumatoid arthritis, an autoimmune disease in which the cartilage and bones of joints become damaged, resulting in malformation of the hands.





AIDS

Since the epidemic was first recognized in 1981, AIDS (acquired immunodeficiency syndrome) has killed more than 30 million people worldwide, and more than 33 million people are currently living with the AIDS virus, HIV. In 2009, 6 million people were newly infected with HIV, and nearly 2 million died, including over 300,000 children under the age of 15. The vast majority of HIV infections and AIDS deaths occur in sub-Saharan Africa and southeastern Asia.

HIV is deadly because it destroys the immune system, leaving the body defenseless against most invaders. HIV can infect a variety of cells, but it most often attacks helper T cells—the cells that activate other T cells and B cells (see Figure 24.12). As HIV depletes the body of helper T cells, both the cell-mediated and humoral immune responses are severely impaired. Death usually results not from HIV itself but from another infectious agent or from cancer. The name AIDS refers to the fact that the disease is *acquired* through an infection that results in severe *immunodeficiency* due to a lack of helper T cells and presents as a *syndrome*, a combination of symptoms. (See Figure 10.32 to review the course of cell infection by HIV.)

Education is the best weapon against the spread of AIDS. Safe sex behaviors, such as reducing promiscuity and using condoms, can save many lives. (Chapter 26 includes further discussion of AIDS prevention.)



HIV and AIDS EVOLUTION CONNECTION

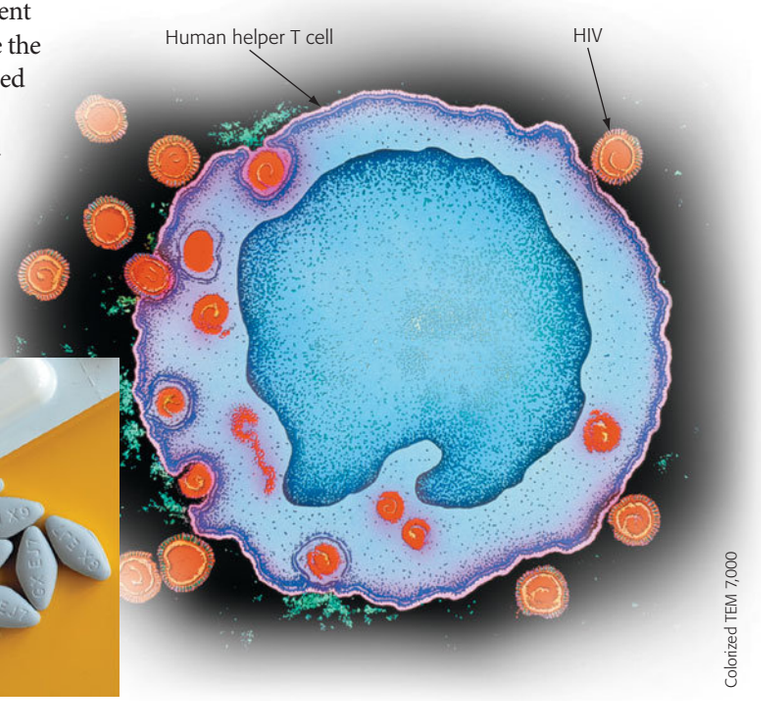
HIV Evolution

Throughout this chapter, we have returned to the topic of HIV and AIDS as a way to highlight the importance of the immune system. To understand why HIV is so harmful, we need to keep in mind biology's unifying theme of evolution. As HIV reproduces, frequent mutations generate new strains of the virus. In fact, HIV has one of the fastest rates of mutation of any pathogen ever studied. This startling fact has led researchers to view evolution of drug-resistant HIV strains as the main obstacle to eradicating AIDS.

At one time, there was great hope that a "cocktail" of three anti-AIDS drugs, each of which attacks a different part of the HIV life cycle, could completely eliminate the virus in an infected person **(Figure 24.17)**. It was hoped that virus strains resistant to one drug would be defeated by another. Such hope greatly underestimated the ability of HIV to evolve. Although people with access to such drugs do survive much longer and have a greatly improved quality of life, drug resistance to even multidrug treatments has evolved in some HIV strains. Thus, the virus is usually not eliminated from a patient's immune system. Although current HIV treatment prolongs the life of HIV-positive people, it is not a cure for AIDS.

Disturbingly, drug-resistant HIV strains are now being found in newly infected patients. This demonstrates that HIV is adapting through natural selection to a changing environment—one in which drug treatments are widely available. In other words, the presence of anti-AIDS drugs in the environment has favored the spread of drug-resistant strains. For now, the battle continues, with medical science on one side and the constantly evolving HIV on the other.





► **Figure 24.17 Anti-AIDS drugs.** A three-drug cocktail can help slow, but usually not eliminate, infection by HIV (virus particles shown on the T cell at right).

Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Innate Defenses

The human body contains two lines of defense (external barriers and internal defenses) that are innate, fully ready to respond before an invader has been encountered.

INNATE DEFENSES			
External	**Internal**		
• Skin • Mucous membranes • Secretions	White blood cells	Defensive proteins	The inflammatory response
	• Phagocytic cells • Natural killer cells	• Interferons • Complement proteins	• Involves chemical signals and phagocytic cells

The Lymphatic System

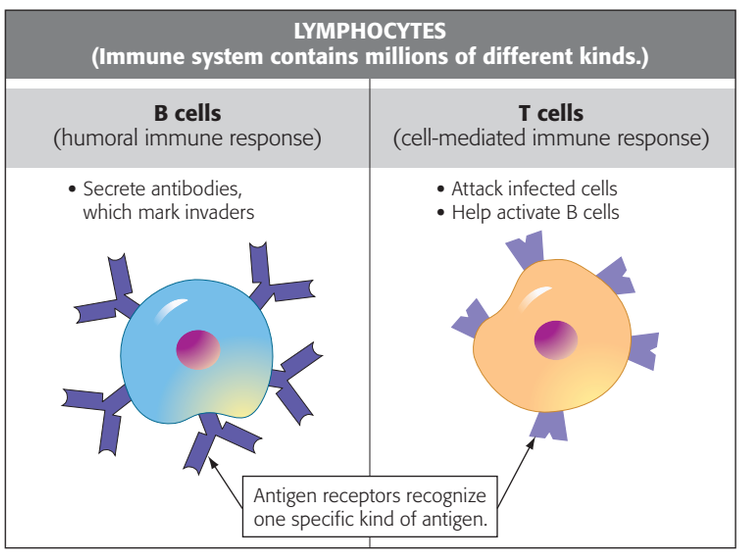
The lymphatic system is a network of lymphatic vessels and organs involved in both innate and adaptive defenses. The vessels collect fluid from body tissues and return it to the blood. The lymphatic organs, including the lymph nodes, are packed with white blood cells that fight infections.

Adaptive Defenses

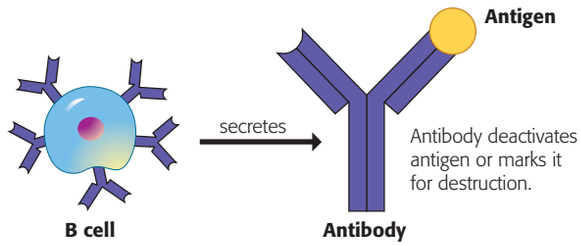
The adaptive defenses consist of a large collection of lymphocytes, white blood cells that respond to specific invaders. Antigens are molecules that elicit responses from lymphocytes.

Recognizing the Invaders

Two kinds of lymphocytes carry out the adaptive immune response to specific invaders carrying nonself molecules.

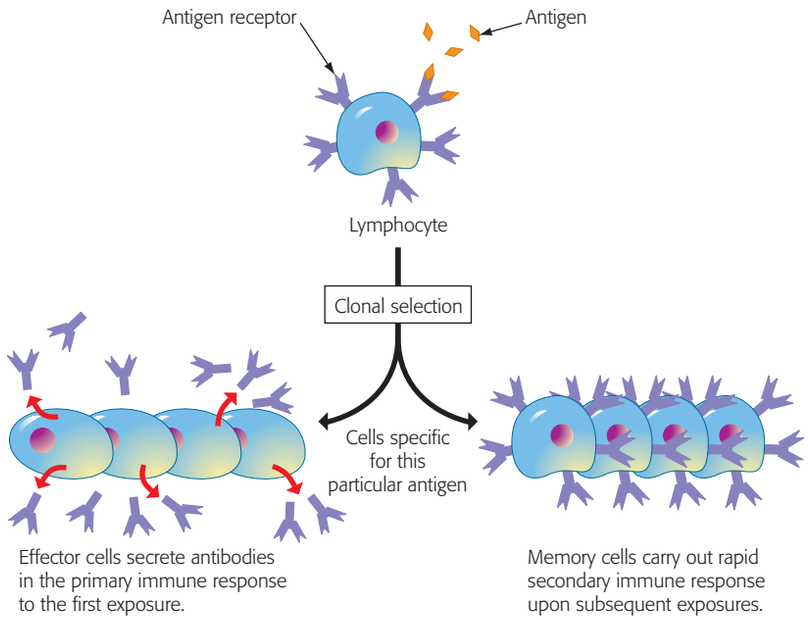


Antibodies recognize antigens through specific binding, which can trigger destruction of the antigen-bearing molecule or cell by several mechanisms. An antibody molecule has four polypeptide chains arranged in a Y shape, with the antigen-binding sites at the tips of the arms of the Y.



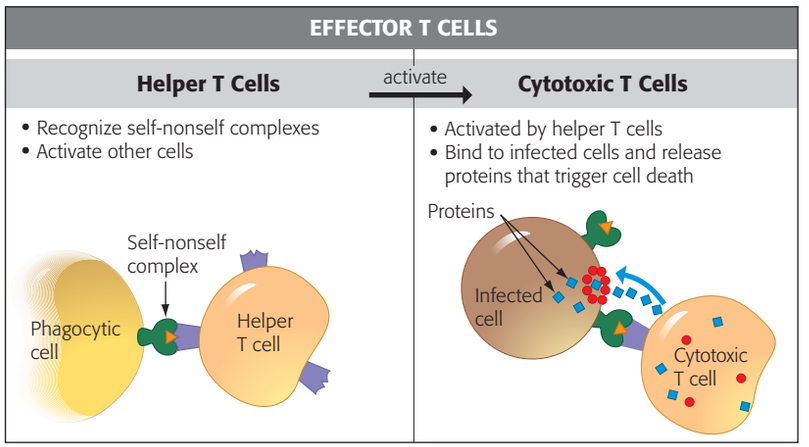
Responding to the Invaders

When an antigen enters the body, it activates only lymphocytes with complementary receptors, a process called clonal selection.



The immune system reacts to antigens and "remembers" an invader. Helper T cells and cytotoxic T cells are the main effector cells in the cell-mediated immune response. Helper T cells also stimulate the humoral immune response, the release of antibodies into body fluids (blood and lymph) by effector B cells. The cell-mediated immune response typically involves a phagocytic cell displaying a foreign antigen (a nonself molecule) and one of the body's own self proteins to a helper T cell. The helper T cell's receptors

recognize the self-nonself complexes, and the interaction activates the helper T cell. In turn, the helper T cell can activate cytotoxic T cells with the same receptors (and can stimulate B cell activation as well). Cytotoxic T cells bind to and destroy infected body cells displaying both self proteins and foreign antigens.



Immune Disorders

Allergies

Allergies are abnormal sensitivities to otherwise harmless antigens, known as allergens. An allergic reaction produces inflammatory responses that result in uncomfortable and sometimes dangerous symptoms.

Autoimmune Diseases

The immune system normally reacts only against nonself substances (foreign molecules and cells), not against self (the body's own molecules). It generally rejects transplanted organs, whose cells lack the recipient's unique "fingerprint" of self proteins. In autoimmune diseases, the system turns against some of the body's own molecules.

Immunodeficiency Diseases

In immunodeficiency diseases, immune components are lacking, and infections recur. Immunodeficiencies may arise through inborn genetic mutations or through disease.

AIDS

AIDS is a worldwide epidemic that kills millions of people each year. HIV, the AIDS virus, attacks helper T cells, crippling both the cell-mediated and humoral immune responses. Practicing safer sex could save many lives.

SELF-QUIZ

1. Molecules that elicit a response from lymphocytes are called _____. Proteins secreted by the immune system that bind to these molecules are called_____.
2. Classify each of the following components of the immune system as being an innate defense or adaptive defense.
   a. natural killer cells
   b. complement proteins
   c. antibodies
   d. inflammation
   e. interferons
   f. cytotoxic T cells
   g. helper T cells
3. Which of the following best describes the difference in the way B cells and T cells deal with invaders?
   a. B cells provide permanent immunity; T cells provide temporary immunity.
   b. B cells send out antibodies that bind to invaders; T cells directly engage the invaders.
   c. T cells handle the primary immune response; B cells handle the secondary immune response.
   d. B cells are responsible for the cell-mediated immune response; T cells are responsible for the humoral immune response.
4. What makes a secondary immune response faster than a primary immune response?
5. Match each type of defensive cell with its function or description.

a. lymphocyte	1. attacks infected body cells
b. cytotoxic T cell	2. carries out the humoral immune response
c. helper T cell	3. white blood cell that engulfs cells or molecules
d. phagocytic cell	4. general name for B or T cell
e. B cell	5. initiates the secondary immune response
f. memory cell	6. cell most commonly attacked by HIV

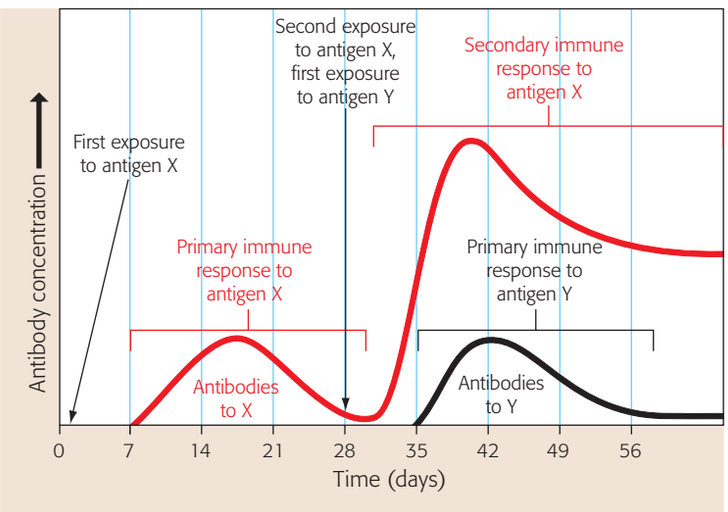
6. Explain how each of the following characteristics of the inflammatory response helps protect the body: swelling, pain, and fever.
7. Why is AIDS deadlier than most other viral diseases?
8. A baby has been born with an immunodeficiency disease. In trying to diagnose the problem, physicians discover that the child is not producing any antibodies. It is most likely that this child is missing what kind of cells?
9. How does the autoimmune disorder lupus affect the immune system?
10. Once vaccinated, you have had a primary exposure to specific antigens. If you ever encounter these antigens again, your body will mount a rapid immune response. The cells that account for this rapid secondary response are called _____. The process that produces these long-lived cells is called _____.

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

11. Most biologists believe that the immune system's defense against infections largely rests on its ability to distinguish self molecules from nonself molecules. This concept seems central to our understanding of immune function. However, like all scientific ideas, it is not beyond question. Several immunologists have developed an alternative hypothesis: that the immune system's effectiveness rests mostly on its ability to recognize damage to body tissues caused by the invaders, not on its ability to recognize nonself. If you were going to test the "damage" hypothesis, what might you look for? Which type of cell would you expect to be directly affected by damaged tissues? Why? Some proponents argue that the "damage" hypothesis makes more sense from an evolutionary perspective, claiming that it is more advantageous for an organism's defense system to respond to tissue damage than to the mere presence of a foreign microbe. Do you agree? Why or why not?

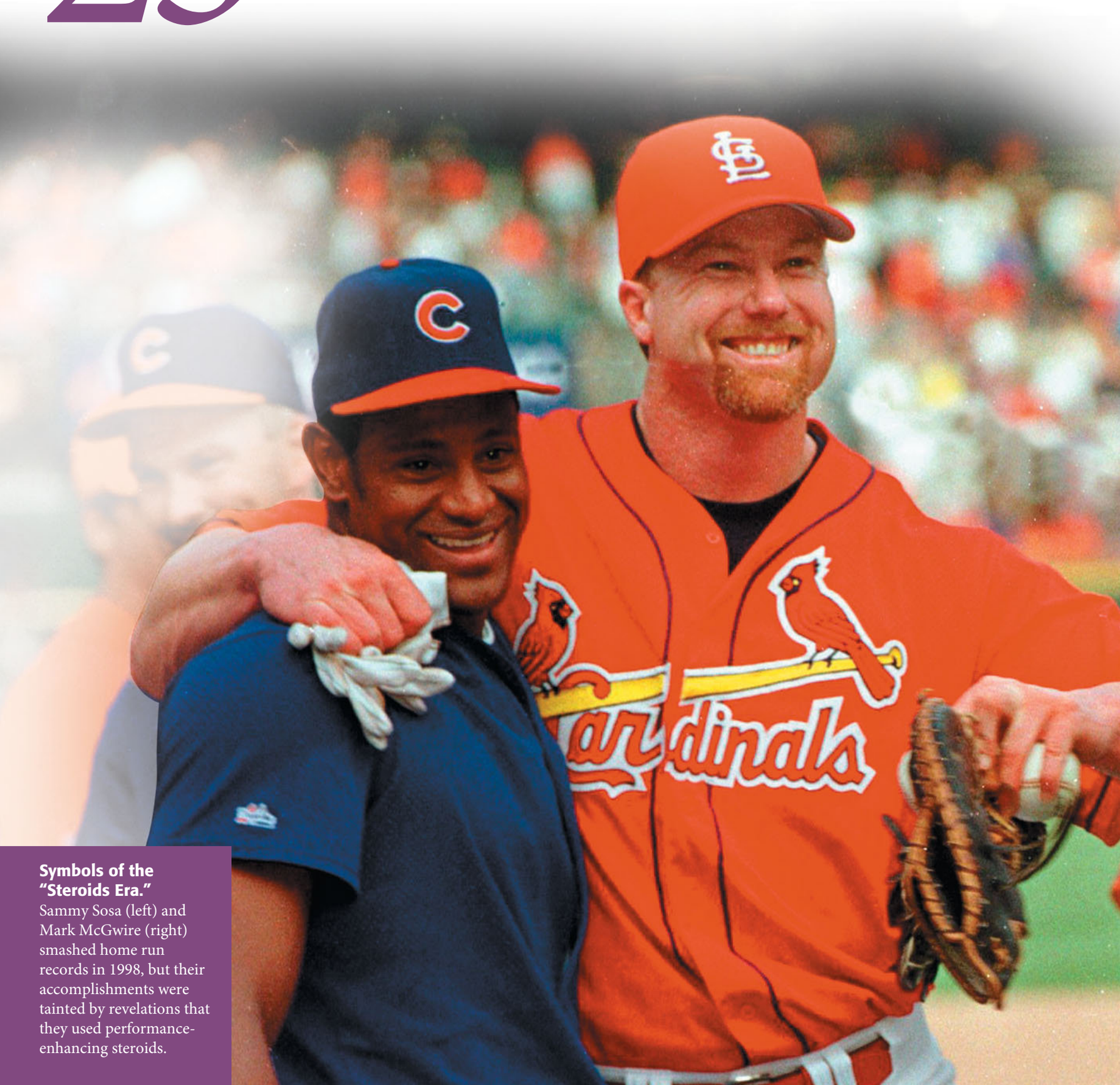
12. The graph below depicts the concentration of two antibodies from a patient's blood: The red line graphs antibody X (produced in response to antigen X), and the black line graphs antibody Y (produced in response to antigen Y). Using your knowledge of clonal selection, explain why these curves have the shapes they do.



BIOLOGY AND SOCIETY

13. Organ donation saves many lives each year. Even though some transplanted organs are derived from living donors, the majority come from patients who die but still have healthy organs that can help a transplant recipient whose cell surfaces have similar sets of proteins. Potential organ donors can fill out an organ donation card to specify their wishes. If the donor is in critical condition and dying, the donor's family is usually consulted to discuss the donation process. Generally, the next of kin must approve before donation can occur, regardless of whether the patient has completed a donor card. In some cases, the donor's wishes are overridden by a family member. Do you think that family members should be able to deny the stated intentions of the potential donor? Why or why not? Have you signed up to be an organ donor? Why or why not?

25 Hormones



Symbols of the "Steroids Era." Sammy Sosa (left) and Mark McGwire (right) smashed home run records in 1998, but their accomplishments were tainted by revelations that they used performance-enhancing steroids.



CHAPTER CONTENTS

Hormones: An Overview 536

The Human Endocrine System 538

CHAPTER THREAD
Steroid Abuse

BIOLOGY AND SOCIETY
Sluggers and Steroids 535

THE PROCESS OF SCIENCE
Do 'Roids Cause Rage? 546

EVOLUTION CONNECTION
Steroids and Male Aggression 547



Steroid Abuse BIOLOGY AND SOCIETY

Sluggers and Steroids

For baseball fans, it was one of the greatest seasons ever. Throughout the spring, summer, and fall of 1998, Mark McGwire, of the St. Louis Cardinals, and Sammy Sosa, of the Chicago Cubs, battled each other to break Roger Maris's 37-year record of 61 home runs in a season. Sosa jumped out to a quick lead with an astonishing 20 home runs in the month of June, one of the greatest offensive outbursts in baseball history. On September 8, McGwire became the first player ever to hit 62 home runs in a season. A few weeks later, Sosa became the first player to hit 65. When the dust settled, McGwire triumphed, logging in an astonishing 70 home runs over the season. Sosa finished with 66, the second highest total ever. Baseball fans reveled in the magic of one of the greatest displays of raw talent ever to grace the diamond.

Or did they? Rumors began to swirl that McGwire and Sosa (as well as many other major leaguers) had artificial help. In 2010, McGwire admitted that he used performance-enhancing steroids over the course of his playing career, including the famous 1998 season. Steroids are hormones, chemical signals that help regulate the body. Although everyone's body naturally produces steroid hormones, some athletes abuse anabolic steroids, synthetic hormones that mimic the male sex hormone testosterone. Taken in large doses, anabolic steroids can increase muscle mass, which can bring greater power to a batter's swing. What about Sosa? It has been widely reported that he failed a test for performance-enhancing drugs in 2003, a claim he does not deny. McGwire and Sosa thus join other all-stars of that era, including Raphael Palmeiro, Jose Canseco, and Alex Rodriguez, all of whom have admitted, or been caught, using banned steroids. McGwire and Sosa's historic race for the home run record is thus viewed by many as yet another chapter in baseball's shameful "steroids era." McGwire has since lamented, "I wish I had never touched steroids. It was foolish and it was a mistake."

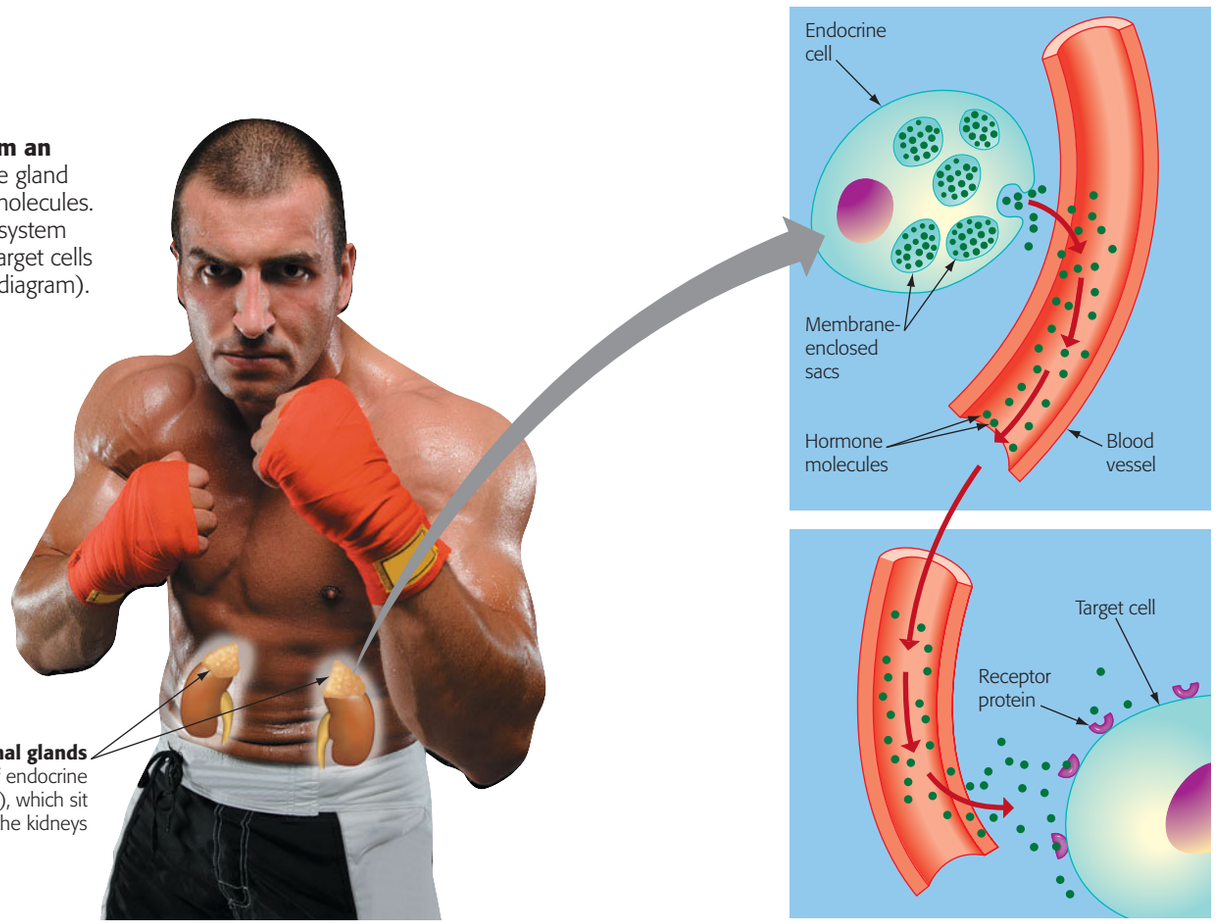
How do steroids affect those who use them? In this chapter, we explore this question by focusing on hormones and the way they maintain homeostasis within the human body. We begin with an overview of how hormones work in all vertebrates and then turn to the major components of the human endocrine system. Along the way, we'll consider many examples of the effects of hormonal imbalance. We'll also further discuss how some people abuse hormones—both natural and artificial—in pursuit of an athletic advantage.

Hormones: An Overview

Hormones are chemical signals produced by most plants (see Table 29.1) and animals. Animal hormones are carried by the circulatory system (usually in the blood) to other parts of the body, where they may communicate regulatory messages. Hormones are made and secreted mainly by organs called **endocrine glands**. Collectively, all hormone-secreting cells make up the **endocrine system**, the body's main system for internal chemical regulation.

The top-right diagram in **Figure 25.1** shows the release of hormone molecules from membrane-enclosed sacs in an endocrine cell. The circulatory system carries hormones throughout the body, but a hormone can only bind to a **target cell** with receptors for that specific hormone (bottom-right diagram). Imagine many keys floating in your bloodstream; each key can only affect those cells with a matching lock. Because hormones reach all parts of the body, the endocrine system is especially important in controlling whole-body activities. For example, hormones govern our metabolic rate, growth (including muscle development, the target of steroid abuse), maturation, and reproduction. In many cases, a tiny amount of a hormone influences the activities of an enormous number of target cells in a variety of organs. Hormones trigger changes in target cells in different ways, depending on whether the hormone is water-soluble or lipid-soluble: Water-soluble hormones trigger responses without entering the cell, whereas lipid-soluble hormones trigger responses after entering the cell.

Water-soluble hormones cannot pass through the oily interior of the phospholipid bilayer of the plasma membrane, but they can bring about cellular changes without entering their target cells **(Figure 25.2)**. To start, 1 a water-soluble hormone (●) binds to a specific receptor protein (●) in the plasma membrane of the target cell. The binding activates the receptor protein, which 2 initiates a signal transduction pathway: a series of changes to molecules that converts a chemical message from outside the cell to a specific response inside the cell. 3 The final relay molecule (●) activates a protein that either carries out a response in the



► **Figure 25.1 Hormone secretion from an endocrine cell.** A cell within an endocrine gland (upper-right diagram) secretes hormone molecules. The hormone is carried via the circulatory system to all cells of the body, but it only affects target cells that have matching receptors (lower-right diagram).

cytoplasm (such as activating an enzyme) or affects gene regulation in the nucleus (such as turning on or off genes). This is a bit like the game of "telephone," with a message passed from one person to the next—but this message is (hopefully) received exactly as sent!

Water-soluble hormones that bind to plasma membrane receptors come in three varieties, all derived from amino acids: amine hormones, which are modified versions of single amino acids; peptide hormones, which are short chains of 3–30 amino acids; and protein hormones, made of polypeptides. An example of a protein hormone is erythropoietin (EPO), which regulates the production of red blood cells. Some athletes abuse EPO as a performance-enhancing drug because it increases their capacity for endurance.

How can hormone abuse lead to blood doping?

In contrast, lipid-soluble hormones pass through the phospholipid bilayer and trigger responses by binding to receptors inside the target cell. Steroid hormones—including natural ones such as the sex hormones (testosterone, estrogen, and progesterone) as well as artificial anabolic steroids—work in this manner. As shown in Figure 25.3, 1 a lipid-soluble hormone (▼) enters a cell by diffusing through the plasma membrane. If the cell is a target cell, the hormone 2 binds to a receptor protein (🟣) in the cytoplasm or nucleus. Rather than triggering a signal transduction pathway, the receptor itself carries the hormone's signal. 3 The hormone-receptor complex attaches to specific sites on the cell's DNA in the nucleus. 4 The binding to DNA turns specific genes on or off.

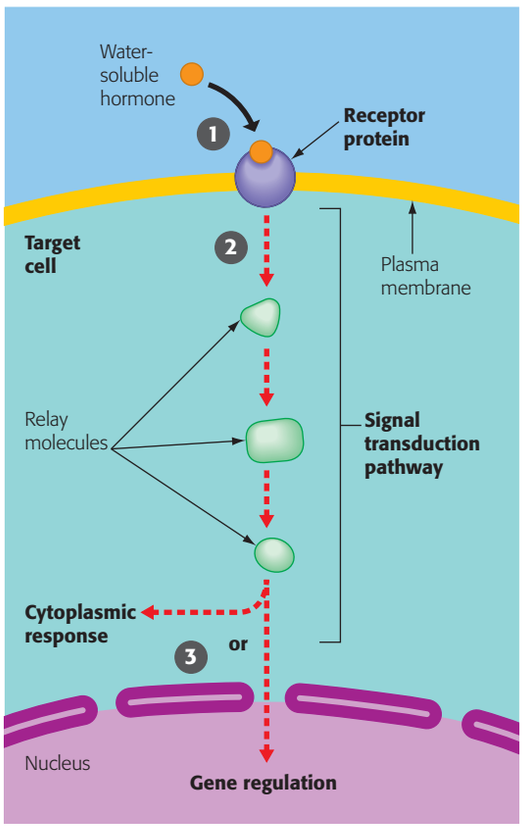
We've now completed an overview of how hormones work. The principles presented so far apply to all vertebrates (as well as many invertebrates). In the next section, we'll take a closer look at the endocrine system of one particular vertebrate: humans. ☑

☑ CHECKPOINT

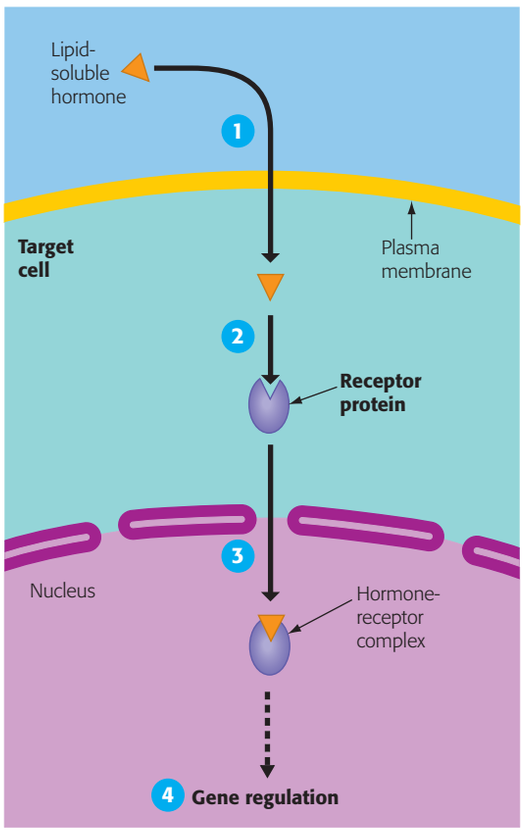
1. Why are hormones particularly useful in carrying signals that affect many different organs?
2. What is the difference in the way that lipid-soluble and water-soluble hormones interact with their target cells?

Answers: **1.** *they are transported in the blood to all parts of the body* **2.** *Lipid-soluble hormones bind to receptors inside the cell, whereas water-soluble hormones bind to receptors in the plasma membrane.*

▼ Figure 25.2 A hormone that binds to a plasma membrane receptor. Hormones that are water-soluble cannot cross the phospholipid bilayer but can bind to membrane receptors outside target cells and activate a signal transduction pathway.



▼ Figure 25.3 A hormone that binds to an intracellular receptor. Hormones that are lipid-soluble can cross the phospholipid bilayer and bind to receptors inside target cells. Steroid hormones and other lipid-soluble hormones affect the cell by turning specific genes on and off.



The Human Endocrine System

The human endocrine system consists of about a dozen major glands. Some of these, such as the thyroid and pituitary glands, are endocrine specialists; that is, their primary function is to secrete hormones into the blood. Several other glands have both endocrine and nonendocrine functions. The pancreas, for example, secretes hormones that influence the level of glucose in the blood and also secretes digestive enzymes into the intestine. Other organs are primarily nonendocrine but have some cells that secrete hormones. For example, the stomach is primarily a digestive organ but also releases ghrelin (the "hunger hormone"), which travels to the brain and stimulates appetite. (As you can imagine, ghrelin is the target of weight loss research, but so far no treatments that interact with it have been developed.)

Can a hormone make you hungry?

Figure 25.4 shows the locations of the major human endocrine glands discussed in this chapter. **Table 25.1** summarizes the actions of the main hormones they produce. The table provides an overview of the human endocrine system, and you may wish to refer to it as you read along through the chapter as we focus on the individual glands and their hormones.

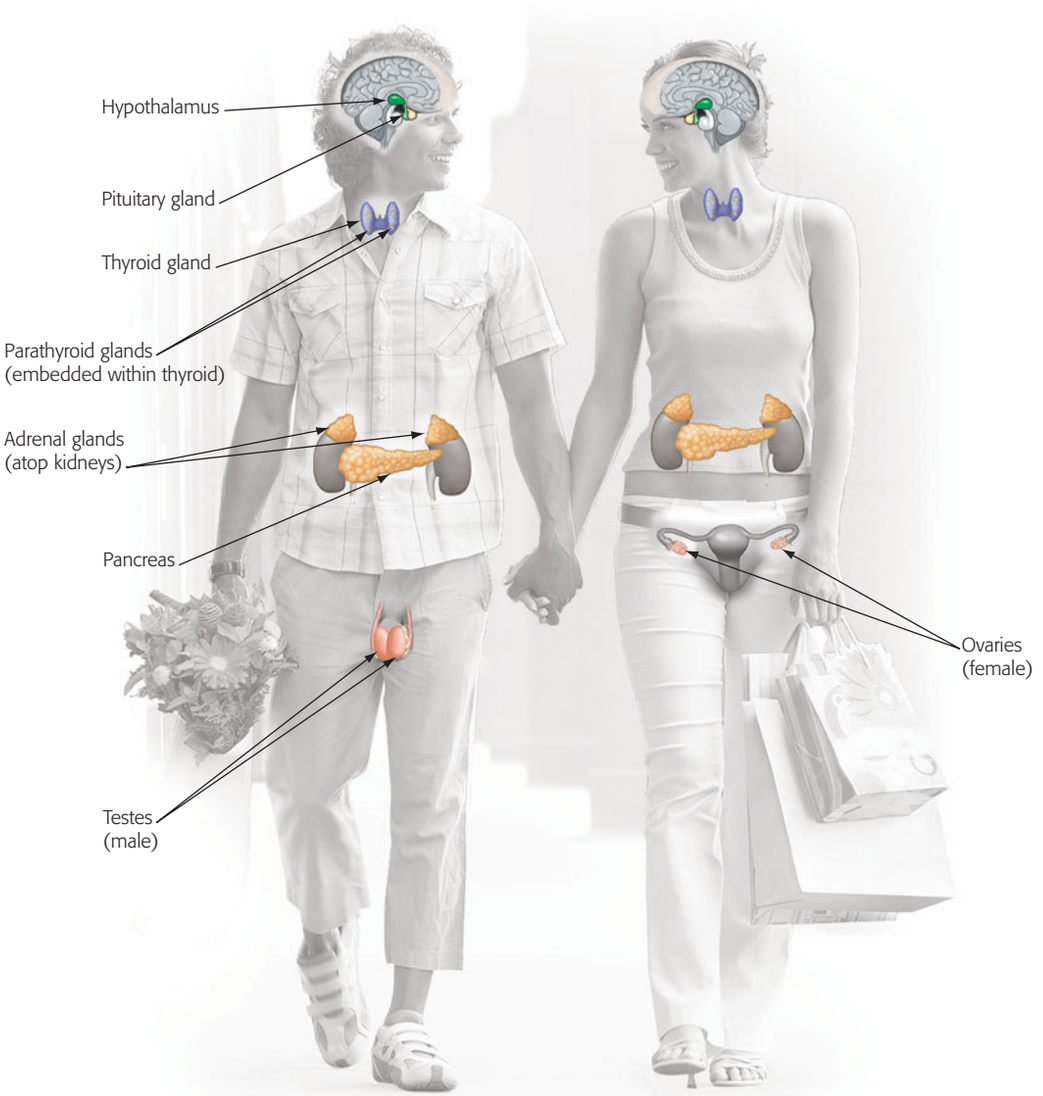
Hormones have a wide range of targets. Some hormones, like the sex hormones, affect most of the tissues of the body. Others, such as glucagon from the pancreas, have only a few kinds of target cells (in this case, liver and fat cells). In some cases, a hormone elicits different responses in different target cells, depending on the type of cell and its signal transduction pathway.

The rest of this section focuses on the major glands of the human endocrine system. For each gland, you'll learn about the hormones it secretes and how these chemicals help the body maintain homeostasis. Keep in mind that this chapter only covers the major endocrine glands and their hormones; there are other hormone-secreting structures—the heart and liver, for example—and dozens of other hormones that we will not discuss. ☑

☑ CHECKPOINT

According to Table 25.1, which endocrine glands secrete steroid hormones?

Answer: just the adrenal glands (specifically the adrenal cortex) and the gonads



► **Figure 25.4 The major endocrine glands in humans.** This figure shows only the major endocrine organs discussed in the text. Several other organs that also have endocrine functions are not shown.

Table 25.1 Major Human Endocrine Glands and Some of Their Hormones

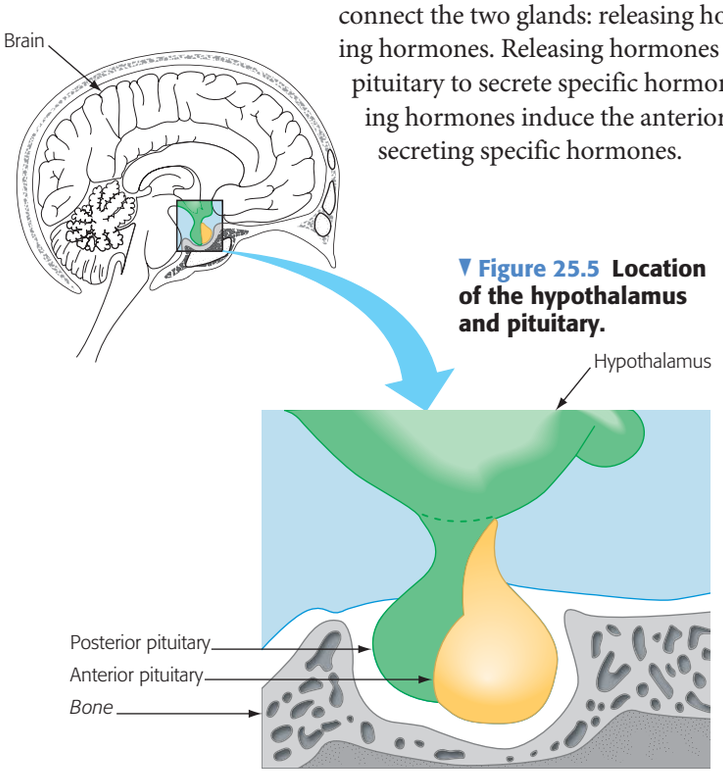
Gland	Hormone	Chemical Class	Representative Actions	Regulated By
Hypothalamus 	Hormones released by the posterior pituitary and hormones that regulate the anterior pituitary (see below)			
Pituitary gland Posterior pituitary (releases hormones made by hypothalamus) 	Oxytocin (see Chapter 26)	Peptide	Stimulates contraction of uterus and mammary gland cells	Nervous system
	Antidiuretic hormone (ADH)	Peptide	Promotes retention of water by kidneys	Water/salt balance
Anterior pituitary 	Follicle-stimulating hormone (FSH)	Protein	Stimulates production of ova and sperm	Hypothalamic hormones
	Luteinizing hormone (LH)	Protein	Stimulates ovaries and testes	Hypothalamic hormones
	Human growth hormone (HGH)	Protein	Stimulates growth (especially bones) and metabolic functions	Hypothalamic hormones
	Prolactin (PRL; see Chapter 26)	Protein	Stimulates milk production	Hypothalamic hormones
	Thyroid-stimulating hormone (TSH)	Protein	Stimulates thyroid gland	Thyroxine in blood; hypothalamic hormones
	Adrenocorticotropic hormone (ACTH)	Peptide	Stimulates adrenal cortex to secrete glucocorticoids	Glucocorticoids; hypothalamic hormones
	Endorphins	Peptides	Mask pain	Brain
Thyroid gland 	Triiodothyronine (T_3) and thyroxine (T_4)	Amines	Stimulate and maintain metabolic processes	TSH
	Calcitonin	Peptide	Lowers blood calcium level	Calcium in blood
Parathyroid glands 	Parathyroid hormone (PTH)	Peptide	Raises blood calcium level	Calcium in blood
Pancreas 	Insulin	Protein	Lowers blood glucose level	Glucose in blood
	Glucagon	Protein	Raises blood glucose level	Glucose in blood
Adrenal glands Adrenal medulla 	Epinephrine (adrenaline) and norepinephrine (noradrenaline)	Amines	Raise blood glucose level; increase metabolic activities; constrict certain blood vessels	Nervous system
Adrenal cortex 	Glucocorticoids	Steroids	Raise blood glucose level	ACTH
Gonads Testes 	Androgens (testosterone)	Steroids	Support sperm formation; promote development and maintenance of male secondary sex characteristics	FSH and LH
Ovaries 	Estrogens	Steroids	Stimulate uterine lining growth; promote development and maintenance of female secondary sex characteristics	FSH and LH
	Progestins	Steroids	Promote uterine lining growth	FSH and LH

The Hypothalamus and Pituitary Gland



The **hypothalamus** is a gland that acts as the main control center of the endocrine system **(Figure 25.5)**. As part of the brain, the hypothalamus receives information from nerves about the internal condition of the body and about the external environment. It then responds by sending out appropriate nervous or endocrine signals. These signals directly control the **pituitary gland**, a pea-sized structure that hangs down from the hypothalamus. In response to signals from the hypothalamus, the pituitary secretes hormones that influence numerous body functions. The hypothalamus thus exerts master control over the endocrine system by using the pituitary to relay directives to other glands.

As Figure 25.5 shows, the pituitary gland consists of two distinct parts: a posterior lobe and an anterior lobe, both tucked in a pocket of skull bone just under the hypothalamus. The **posterior pituitary** is actually an extension of the hypothalamus that stores and secretes hormones made in the hypothalamus. In contrast, the **anterior pituitary** synthesizes and secretes its own hormones directly into the blood. The hypothalamus exerts control over the anterior pituitary by secreting two kinds of hormones into short blood vessels (not illustrated) that connect the two glands: releasing hormones and inhibiting hormones. Releasing hormones stimulate the anterior pituitary to secrete specific hormones, whereas inhibiting hormones induce the anterior pituitary to stop secreting specific hormones.



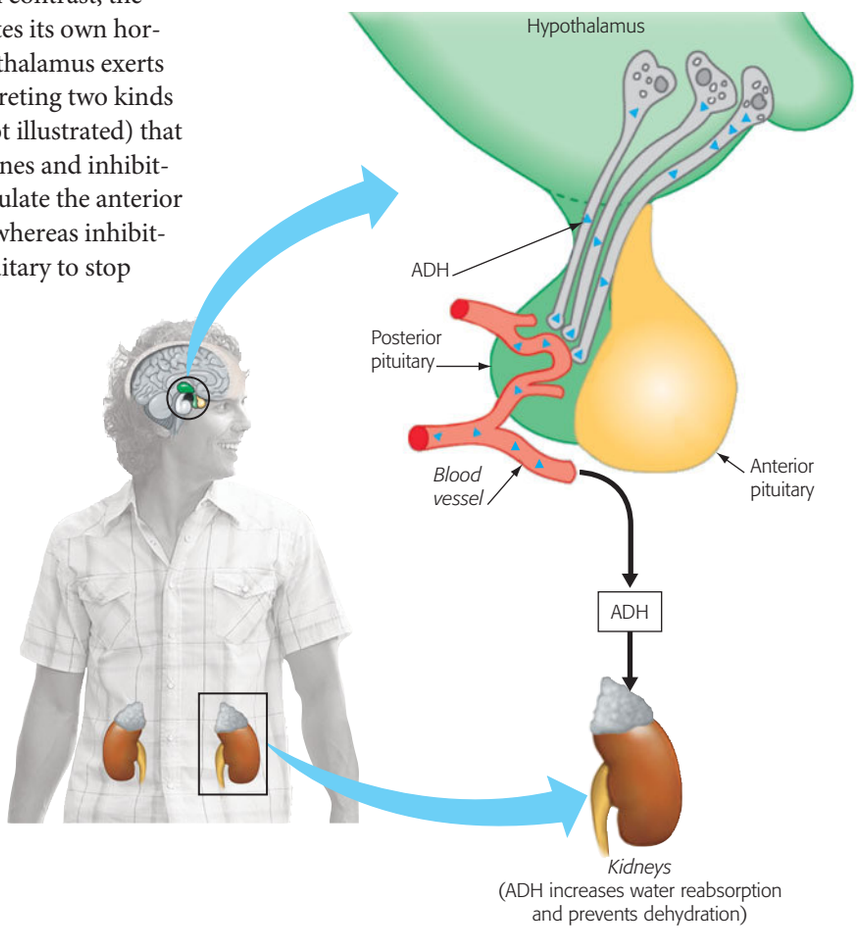
▼ Figure 25.5 Location of the hypothalamus and pituitary.

Figure 25.6 shows how the hypothalamus operates through the posterior pituitary to direct the activity of the kidneys. The hypothalamus makes antidiuretic hormone (ADH) (▲), which is stored and released by the posterior pituitary. ADH helps kidney cells reabsorb water, preventing dehydration by decreasing urine volume when the body needs to retain water (see Chapter 21). When the body has too much water, the hypothalamus slows the release of ADH from the pituitary. Some drugs, such as caffeine and alcohol, act as a diuretic by inhibiting the release of ADH, which in turn increases the output of urine. This can lead to dehydration.

Why do caffeinated drinks tend to cause dehydration?

In response to releasing hormones secreted by the hypothalamus, the anterior pituitary synthesizes and releases many different hormones that influence a broad range of body activities. For example, it releases follicle-stimulating hormone (FSH) and luteinizing hormone (LH), which help regulate the menstrual cycle (as you'll see in Chapter 26).

▼ Figure 25.6 ADH and osmoregulation. The hypothalamus regulates water homeostasis by synthesizing ADH. Molecules of this hormone travel via long cellular extensions (gray) to the posterior pituitary, where they are released into the blood. Eventually, the ADH reaches target cells in the kidneys.



No pituitary secretion has a broader effect than the protein called **human growth hormone (HGH)**. Overproduction of HGH in adults results in acromegaly, characterized by enlarged bones in the hands, feet, and face (Figure 25.7a). During childhood and adolescence, high levels of HGH promote the development and enlargement of all parts of the body. If too much HGH is produced in a very young person, usually because of a pituitary tumor, gigantism can result (Figure 25.7b). In contrast, too little HGH during childhood can lead to dwarfism (Figure 25.7c). Administering HGH to children with HGH deficiency can prevent dwarfism. HGH was originally extracted in only minute quantities from the pituitary glands of cadavers, but is now produced in large quantities by genetically engineered bacteria (see Chapter 12). With the increased availability of HGH, some athletes have misused the drug in order to bulk up their muscles. Such abuse is extremely dangerous and can lead to disfigurement, heart failure, and cancer. Consequently, the use of HGH is banned by nearly every athletic governing body.



The **endorphins**, another kind of anterior pituitary hormone, are the body's natural painkillers; they mask the perception of pain. Some researchers speculate that the so-called runner's high results partly from the release of endorphins when stress and pain in the body reach critical levels. The release of endorphins may also produce pleasant feelings during such diverse activities as meditation, acupuncture treatments, and even eating very spicy foods. ☑

☑ CHECKPOINT

Which gland is the primary control center for the entire endocrine system? Which gland is directly controlled by this master gland?

Answer: the hypothalamus; the pituitary

▼ **Figure 25.7 Pituitary growth hormone disorders.**



(a) Overproduction of HGH during adulthood. Overproduction of HGH later in life causes acromegaly. The most common symptom of this disease is enlargement of the hands and face, as seen here in this X-ray.



(b) Overproduction of HGH during development. Yao Defeng's extreme size (7 feet 9 inches) is due to a benign brain tumor that results in excess growth hormone.



(c) Underproduction of HGH during development. The body of actor Peter Dinklage, like those of other dwarfs, produced low amounts of GH during childhood.

The Thyroid and Parathyroid Glands



Your **thyroid gland** is in your neck, just under your larynx (voice box). The thyroid produces hormones (thyroxine and triiodothyronine) that increase oxygen consumption and metabolic rate in all the cells of your body. These thyroid hormones also play crucial roles in development and maturation, particularly of the bone and nerve cells. Insufficient levels of the thyroid hormones in the blood (hypothyroidism) or excess levels (hyperthyroidism) can result in serious metabolic disorders. Fortunately, thyroid disorders can be treated easily.

Hypothyroidism (too little thyroid hormones) can result from dietary deficiencies or from a defective thyroid gland. To produce thyroxine and triiodothyronine, the thyroid requires the element iodine. If too little iodine is available, insufficient quantities of these thyroid hormones are produced. This underproduction interrupts feedback loops that control thyroid activity, causing overstimulation and swelling of the thyroid gland. A type of dietary hypothyroidism called goiter has been reduced in many industrialized nations by the incorporation of iodine into table salt (see Figure 2.3). Unfortunately, goiter still affects many people in less industrialized nations.

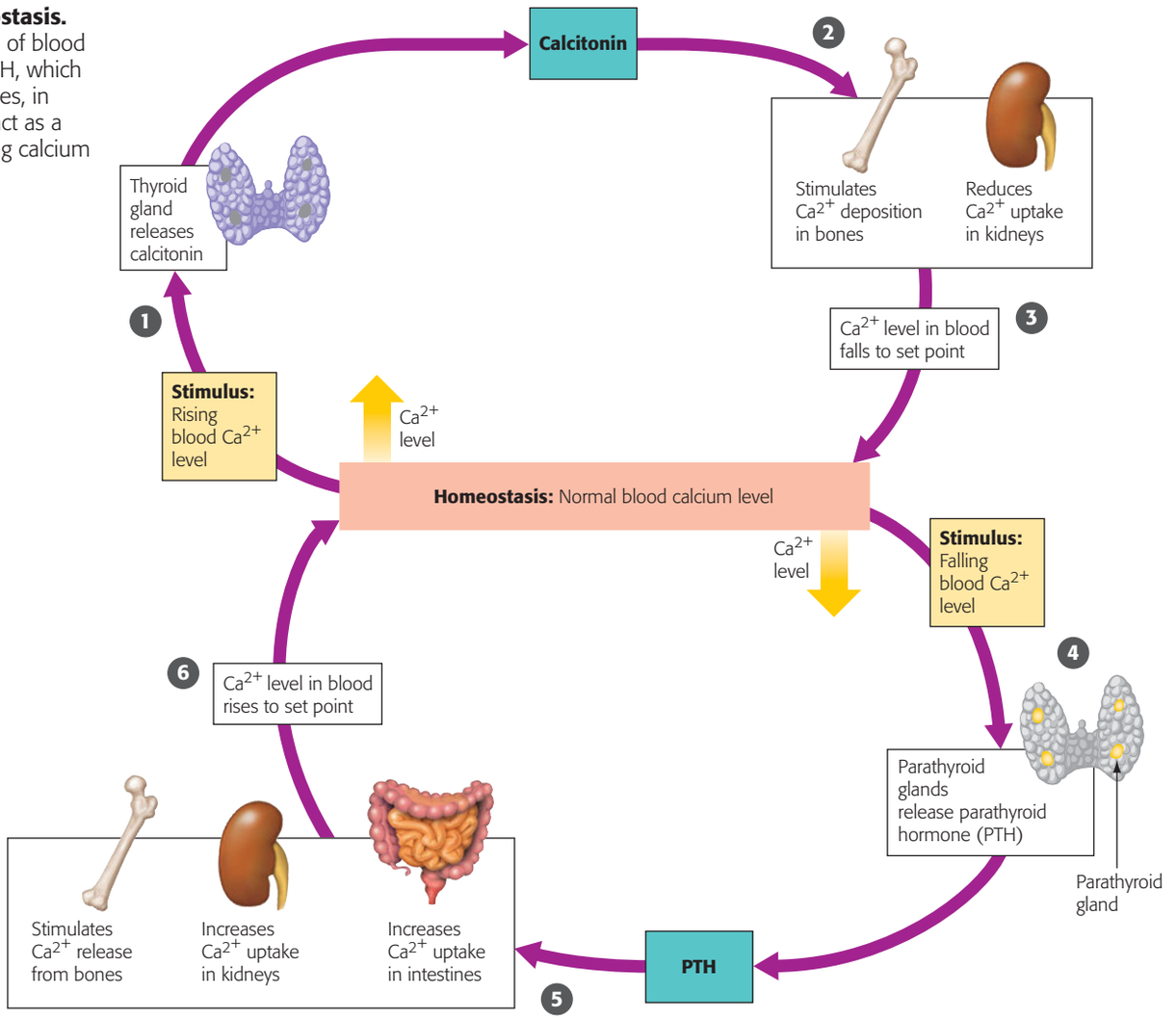
A common form of hyperthyroidism (overproduction of thyroid hormones) is Graves' disease, characterized by overheating, profuse sweating, high blood pressure, and protruding eyeballs. One treatment takes advantage of the fact that the thyroid accumulates iodine: Patients drink a solution containing a small dose of radioactive iodine, which kills off just enough cells to reduce thyroid output and relieve symptoms.

Why would someone purposefully drink radioactive iodine?

Embedded within the thyroid are four disk-shaped **parathyroid glands**. The thyroid and parathyroid glands function in calcium homeostasis, keeping the concentration of calcium ions (Ca^{2+}) in the blood within a narrow range. An appropriate level of calcium in the blood and interstitial fluid is essential for many of your body's functions. Without calcium, nerve signals cannot be transmitted from cell to cell, your muscles cannot function properly, your blood cannot clot, and your cells cannot transport molecules across their membranes. **Calcitonin** from the thyroid and **parathyroid hormone (PTH)** from the parathyroids regulate the blood calcium level. They are said to be **antagonistic hormones** because they have opposite effects: Calcitonin lowers the calcium level in the blood, whereas PTH raises it.

As **Figure 25.8** indicates, calcitonin and PTH operate by means of feedback systems that keep the calcium level near the homeostatic set point. (1) A rise in the blood Ca^{2+} level above the homeostatic set point induces the thyroid gland to secrete calcitonin. (2) Calcitonin, in turn, has two main effects: It causes more Ca^{2+} to be deposited in the bones, and it makes the kidneys reabsorb less Ca^{2+} as they form urine. (3) The result is a lower Ca^{2+} level in the blood. (4) When the blood Ca^{2+} level drops below the set point, the parathyroids release PTH into the blood. (5) PTH stimulates the release of Ca^{2+} from bones and increases Ca^{2+} uptake by the kidneys and intestines, (6) raising the calcium level.

In summary, a sensitive balancing system maintains calcium homeostasis. Failure of the system can have far-reaching effects in the body. For example, a shortage of PTH causes the blood calcium level to drop dramatically, which can lead to tetany, a condition of uncontrollable muscle contractions and potentially fatal convulsions. ✓



► **Figure 25.8 Calcium homeostasis.** This diagram traces the regulation of blood calcium level by calcitonin and PTH, which act antagonistically. Note that bones, in addition to supporting the body, act as a calcium bank, storing and releasing calcium as needed.

✓ CHECKPOINT

Both calcitonin (from the thyroid) and parathyroid hormone (from the parathyroids) regulate blood calcium level. Why are these two hormones said to be antagonistic?

Answer: These two hormones have opposite effects: Calcitonin lowers blood calcium level, whereas PTH raises it.

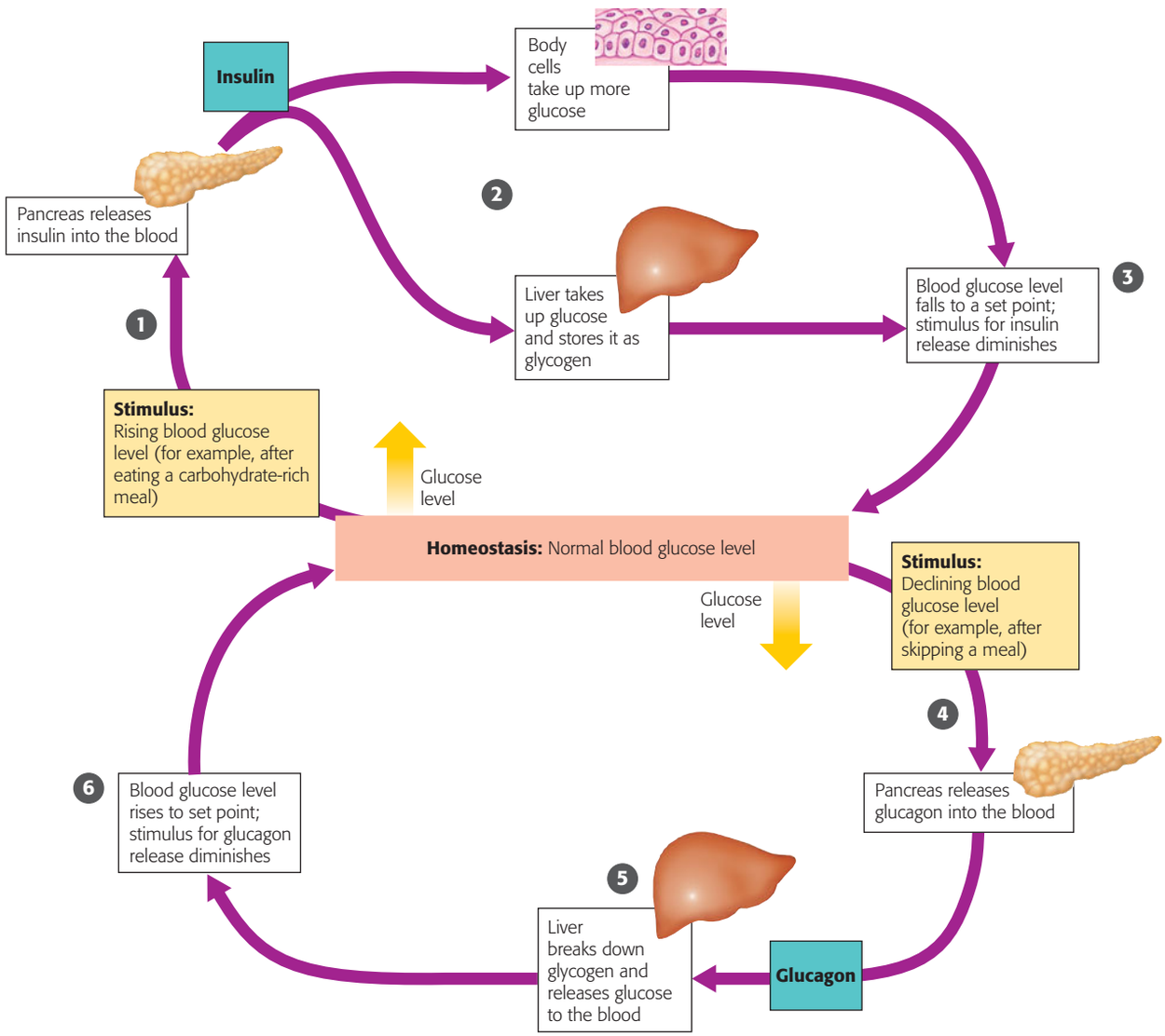
The Pancreas



The **pancreas** produces two hormones that play important roles in managing the body's energy supplies. One of the hormones is **insulin**, a protein hormone produced by clusters of specialized pancreatic cells called islet cells. Other islet cells secrete another protein hormone, called **glucagon**. Insulin and glucagon help maintain a homeostatic balance between the amount of glucose available in the blood and the amount of glucose stored as the polymer glycogen in body cells.

As shown in **Figure 25.9**, insulin and glucagon are antagonistic hormones, countering each other in a feedback circuit that precisely manages the level of glucose in the blood. By negative feedback, the concentration of glucose in the blood determines the relative amounts of insulin and glucagon secreted by islet cells. (1) Rising glucose concentration in the blood—as happens shortly after you eat a carbohydrate-rich meal, for example—stimulates the pancreas to secrete more insulin into the blood. (2) Body cells take up more glucose from the blood, while liver and skeletal muscle cells take up glucose and use it to make glycogen, which they store. (3) As a result, the blood glucose level falls to the set point, and the cells of the pancreas lose their stimulus to secrete insulin.

(4) When the blood glucose level dips below the set point, as it may between meals, pancreatic cells respond by secreting more glucagon. (5) Glucagon is a fuel mobilizer, making liver cells break glycogen down into glucose and release it into the blood. (6) Then, when the blood glucose level returns to the set point, the pancreas slows its secretion of glucagon.



► **Figure 25.9**
Glucose homeostasis. This diagram traces the regulation of blood glucose level by insulin and glucagon, two antagonistic hormones released by the pancreas.

Diabetes mellitus is a serious hormonal disease that affects about 8% of Americans—24 million people—and 6 million of them don't even know they are ill. In diabetes, body cells are unable to absorb glucose from the blood, either because there is not enough insulin in the blood (as in type 1, or insulin-dependent, diabetes) or because the target cells do not respond normally to the insulin in the blood (as in type 2, or non-insulin-dependent, diabetes). A third type of diabetes, called gestational diabetes, can affect any pregnant woman, even one who has never shown symptoms of diabetes before.

In a person with diabetes, cells cannot obtain enough glucose from the blood, even though there is plenty. Starved for fuel, cells are forced to burn the body's supply of fats and proteins. Meanwhile, the digestive system continues to absorb glucose from the diet, causing the glucose concentration in the blood to become dangerously high.

There are treatments for diabetes but no cure. Type 1 patients require regular injections of insulin, usually obtained from genetically modified bacteria **(Figure 25.10)**.

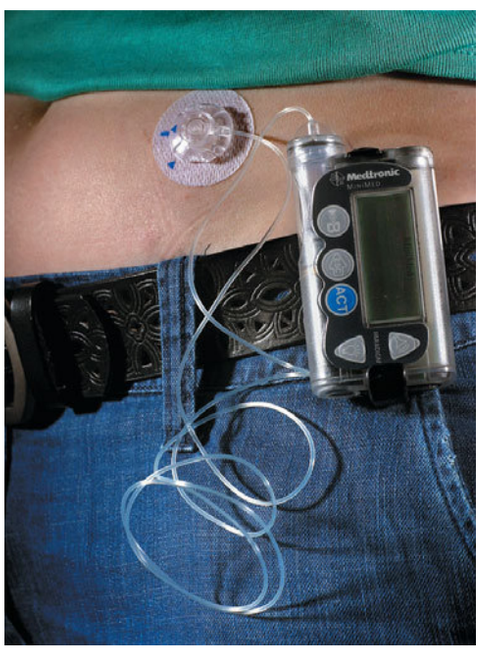
☑ CHECKPOINT

If someone with type 1 diabetes eats a big meal and does not take any medication, what will happen to that person's blood glucose level?

Answer: A person with type 1 diabetes has insufficient insulin in the bloodstream, which results in a high level of glucose in the blood after a meal.

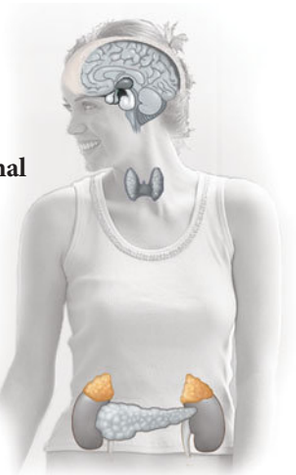
▼ Figure 25.10 Managing diabetes. People with diabetes use glucose meters (top) to measure the amount of glucose in the blood. When needed, injections of insulin (left) can be self-administered. Some people use a glucose pump (right) to both monitor and inject insulin.





Of those Americans who have diabetes, more than 90% have type 2. This form is almost always associated with being overweight and underactive, although whether obesity causes diabetes (and if so, how) remains unknown. Type 2 diabetes can often be managed by controlling sugar intake and by exercising and dieting to reduce weight. However, every year some 300,000 Americans die from diabetes or its complications, which include severe dehydration, cardiovascular and kidney disease, and nerve damage. ☑

The Adrenal Glands



The human body has two **adrenal glands**, one sitting atop each kidney. Each adrenal gland is actually two glands in one: a central portion called the **adrenal medulla** and an outer portion called the **adrenal cortex**. Though the cells they contain and the hormones they produce are different, both the adrenal medulla and the adrenal cortex secrete hormones that enable the body to respond to stress.

You've probably felt your heart beat faster and your skin develop goose bumps when you've sensed danger or approached a stressful situation. Positive emotions, such as extreme pleasure, can produce the same effects. These reactions are triggered by two "fight-or-flight" hormones secreted by the adrenal medulla: **epinephrine** (also called adrenaline) and **norepinephrine**. These two hormones ensure a rapid, short-term response to stress that can be activated in seconds and last for minutes or hours.

Stressful stimuli, whether negative or positive, activate nerve cells in the hypothalamus. As indicated in the left half of **Figure 25.11**, these cells 1 send signals that stimulate the adrenal medulla to 2 secrete epinephrine and norepinephrine (•) into the blood. Epinephrine and norepinephrine both contribute to the short-term stress response by stimulating liver cells to release glucose, making more fuel available for cellular work. They also prepare the body for action by raising blood pressure, breathing rate, heart rate, and metabolic rate. In addition, epinephrine and norepinephrine change blood flow patterns to shuttle blood to where it is most needed: Blood vessels in the brain and skeletal muscles are widened, increasing alertness and the muscles' ability to react to stress, while blood vessels elsewhere are narrowed, reducing activities (such as digestion) that are not immediately involved in the stress response. The short-term stress response occurs and subsides rapidly.

Why might an athlete receive cortisone injections into an injured joint?

In contrast to epinephrine and norepinephrine (secreted by the adrenal medulla), hormones secreted by the adrenal cortex can provide a slower, longer-lasting response to stress that can last for hours or days. As the right half of Figure 25.11 indicates, the hypothalamus 3 secretes a releasing hormone (•) that stimulates the pituitary to 4 secrete a hormone called ACTH (adrenocorticotropic hormone) (•). In turn, ACTH stimulates cells of the adrenal cortex to 5 synthesize and secrete a family of steroid hormones called **corticosteroids** (•), which include the glucocorticoids. The **glucocorticoids** help promote the synthesis of glucose from noncarbohydrates, such as proteins and fats.

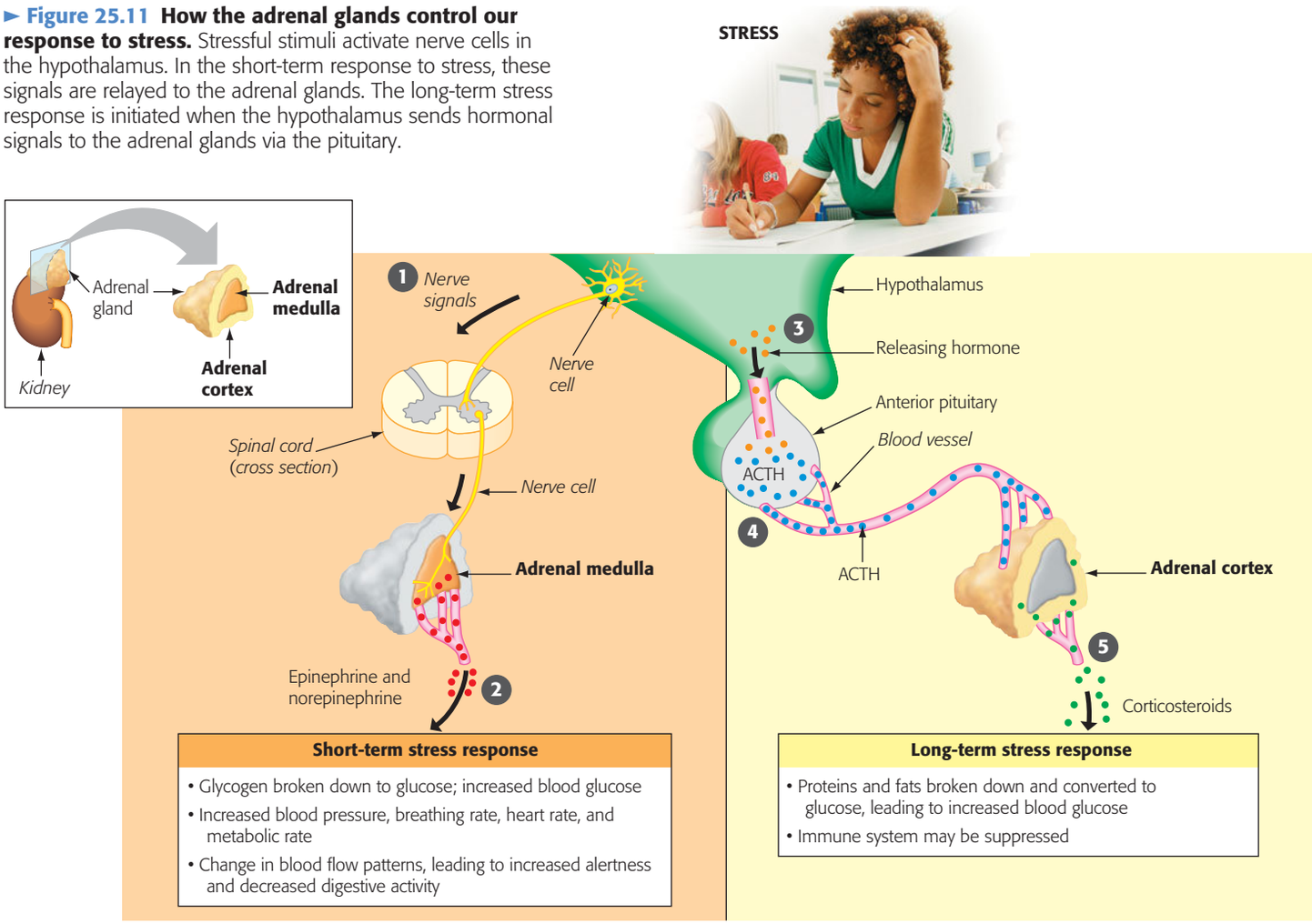
Very high levels of glucocorticoids in the blood can suppress the body's defense system, including the inflammatory response that occurs at infection sites (see Figure 24.4). For this reason, physicians may use glucocorticoids to treat excess inflammation. Cortisone, for example, can be used to treat arthritis. Some professional athletes, such as baseball and football players, often receive cortisone injections into injured joints. With this treatment, the pain usually subsides, but its underlying cause remains. Masking the pain covers up the pain's message—that tissue is damaged and may get worse if not allowed to heal. If an athlete exercises an injured joint before the tissue has recovered, the added stress can cause more serious and longer-lasting damage. ☑

☑ CHECKPOINT

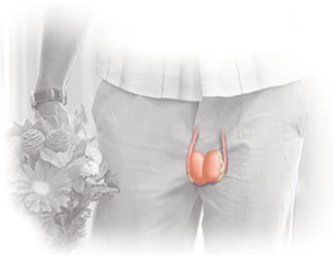
Which hormones regulate the short-term stress response? What family of hormones regulates the long-term stress response?

Answer: epinephrine and norepinephrine; corticosteroids

► **Figure 25.11 How the adrenal glands control our response to stress.** Stressful stimuli activate nerve cells in the hypothalamus. In the short-term response to stress, these signals are relayed to the adrenal glands. The long-term stress response is initiated when the hypothalamus sends hormonal signals to the adrenal glands via the pituitary.



The Gonads





Sex hormones are steroid hormones that affect growth and development and regulate reproductive cycles and sexual behavior. Under the direction of the hypothalamus and pituitary gland, the **gonads**, or sex glands (ovaries in the female and testes in the male), secrete sex hormones in addition to producing gametes (sperm and egg).

The gonads of humans produce three major categories of sex hormones: androgens, estrogens, and progestins. Both men and women have all three. In women, estrogens are found in higher concentrations than androgens. **Estrogens** maintain the female reproductive system and promote the development of such female features as breasts and wider hips. **Progestins**, such as progesterone, are primarily involved in preparing the uterus to support a developing embryo.

Men have a high ratio of androgens to estrogens. **Androgens**, mainly testosterone, stimulate the development and maintenance of the male reproductive system. Androgens produced by male embryos during the 7th week of development stimulate the embryo to develop into a male rather than a female. During puberty, a high concentration of testosterone triggers the development of male characteristics, such as a lower-pitched voice, facial hair, and large skeletal muscles.

Anabolic steroids are artificial hormones that mimic the structure and function of testosterone and can therefore allow a person to build muscle quickly. Some athletes abuse "designer steroids"—anabolic steroids specifically designed to elude drug tests. What effects might steroid abuse have? We explore that question next. ☑

☑ CHECKPOINT

How could a hormonal imbalance result in a person who is genetically male but physically female?

Answer: If cells within a male embryo do not secrete testosterone at the proper time during development or the embryo's other cells lack testosterone receptors, the embryo will develop into a female despite being genetically male.



Steroid Abuse THE PROCESS OF SCIENCE

Do 'Roids Cause Rage?

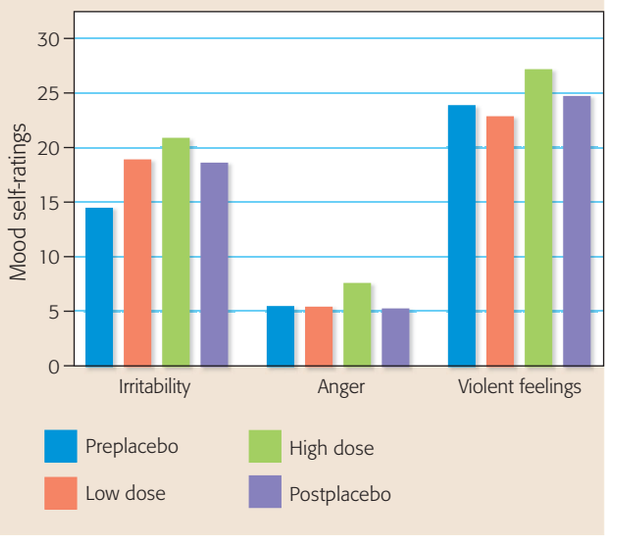
For years, doctors made **observations** of an apparent link between abuse of anabolic steroids and violent mood swings, a phenomenon commonly referred to as "'roid rage." But such a link is hard to clearly establish. Occasional reports (a type of data referred to as "anecdotal evidence") are not subject to analysis by the scientific method and therefore are not considered valid evidence. So how can such claims be tested?

A group of doctors at the National Institutes of Health asked the **question**: Could they measure a relationship between steroids and mood in the lab? Their **hypothesis** was that the administration of increasing doses of steroids to volunteers would produce measurable changes in behavior. Their **prediction** was that they could document mood swings resulting from anabolic steroid injection.

For their **experiment**, they recruited 20 male volunteers between the ages of 18 and 42, none of whom had a history of drug abuse or psychiatric problems. The research participants were given a placebo drug with no steroids (days 1–3), a low dose of steroids (days 4–6), a high dose of steroids (days 7–9), and then a placebo (days 10–12). Throughout the study, the participants were observed continuously and questioned three times a day using standard psychiatric tests that measure mood and behavior.

The **results** of the experiment revealed a significant increase in ratings for hostility, anger, and violent feelings during the high-dose period (**Figure 25.12**). Even though the sample size was small, the researchers noted that their participants received doses well below levels reported taken by some abusers and that the test participants used just a single drug (while some athletes abuse several at once), hinting that real-world abuse could produce even stronger mood swings. Together with many similar studies, the data suggest a link between the abuse of anabolic steroids and violent behavior.

▼ Figure 25.12 The mood-altering effects of anabolic steroids. Each set of bars represents one measure of mood. Each color represents one dosage state. Notice the increased scores during the high-dose period (the third bar in each set).





Steroid Abuse EVOLUTION CONNECTION

Steroids and Male Aggression

Among human males, the primary role of testosterone and other androgens is to promote the development and maintenance of male reproductive anatomy and secondary sexual characteristics (such as facial hair). Androgens play a similar role—promoting uniquely male characteristics—in many species. In fact, research has established that the process of sex determination by androgens occurs in a highly similar manner in all vertebrates, suggesting that androgens had this role early in evolution.

Androgens have been shown to produce a wide variety of effects in different species. In many vertebrates, they are responsible for male vocalizations, such as the territorial songs of birds and the mating calls of frogs. As we have discussed, androgens are connected with aggressive behavior—and not just in people. For example, researchers have measured androgens in a type of cichlid fish called the Mozambique tilapia, a native of eastern Africa found in many home aquariums. Researchers have found elevated androgen levels in males engaged in territorial battles; the victor tends to be the one with the higher level. And in male elephant seals, androgens promote the development of bodies weighing more than 2 tons and aggressive behavior toward other males. These males fight by slamming their bodies against each other **(Figure 25.13)**. After a fight, one male will have established dominance over the other, earning the right to mate with many females, an obvious advantage in terms of Darwinian fitness. Thus, the idea that steroid abuse can lead to aggressive behavior may have an evolutionary basis.

The roles that androgens play among vertebrates illustrate two central aspects of life that result from Darwinian evolution: unity (a consistent effect on the development of the male gonads) and diversity (the variety of secondary effects). The universal nature of gonad development is a strong indication that androgen regulation was an early evolutionary adaptation among vertebrates. But over millions of years of evolution, the specific effects of androgens changed in response to varied environments.



► **Figure 25.13** **Male elephant seals battling for dominance.**

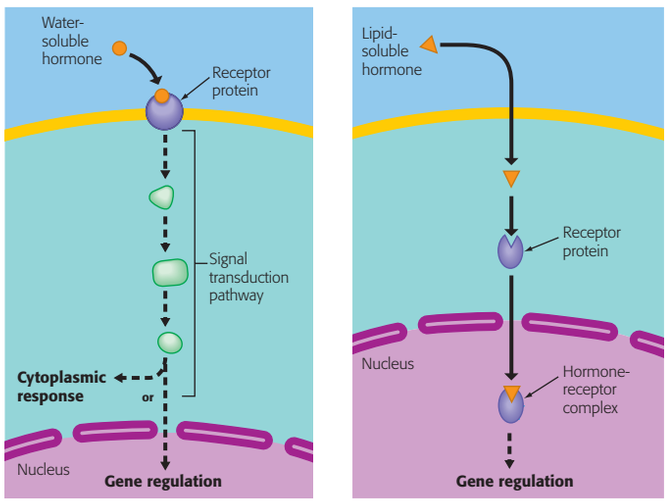
Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Hormones: An Overview

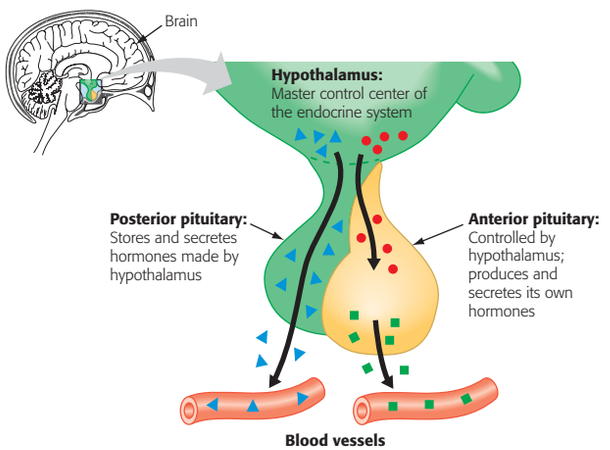
Hormones are chemical signals carried by the circulatory system that communicate regulatory messages throughout the body. The endocrine system consists of a collection of hormone-secreting cells and is the body's main system for internal chemical regulation, particularly of whole-body activities such as growth, reproduction, and control of metabolic rate. Endocrine glands are the primary sites of hormone production and secretion. Changes in target cells are triggered either indirectly by water-soluble hormones or directly by lipid-soluble hormones.



The Human Endocrine System

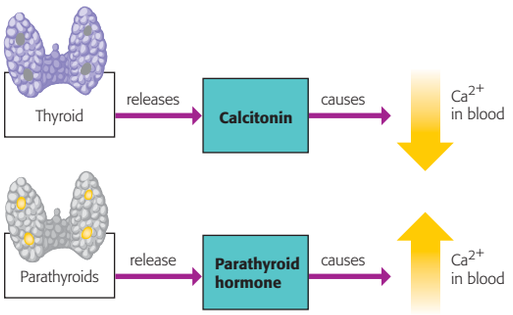
The human endocrine system consists of about a dozen glands that secrete several dozen hormones. These glands and hormones, such as those summarized in Figure 25.4 and Table 25.1, vary widely in their functions, means of regulation, and targets.

The Hypothalamus and Pituitary Gland



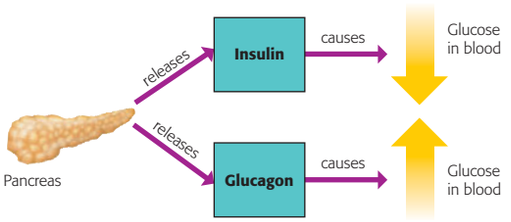
The Thyroid and Parathyroid Glands

Hormones from the thyroid gland regulate an animal's development and metabolism. Too little thyroid hormone in the blood (hypothyroidism) or too much (hyperthyroidism) can lead to metabolic disorders. Blood calcium level is regulated by antagonistic hormones.



The Pancreas

The pancreas secretes two antagonistic hormones, insulin and glucagon, that control the level of glucose in the blood. Insulin signals cells to take up glucose and the liver to store glucose. Glucagon causes the liver to release stored glucose into the blood. Diabetes mellitus results from a lack of insulin (type 1 diabetes) or a failure of cells to respond to it (type 2 diabetes).



The Adrenal Glands

Hormones from the adrenal glands help maintain homeostasis when the body is stressed. Nerve signals from the hypothalamus stimulate the adrenal medulla to secrete epinephrine and norepinephrine, which quickly trigger the fight-or-flight response. ACTH from the anterior pituitary causes the adrenal cortex to secrete corticosteroids. Corticosteroids include glucocorticoids, which promote the synthesis of glucose. Glucocorticoids, such as cortisone, relieve inflammation and pain, but they can mask injury and suppress immunity.

The Gonads

Estrogens, progestins, and androgens are steroid sex hormones produced by the ovaries in females and the testes in males. Estrogens and progestins stimulate the development of female characteristics and maintain the female reproductive system. Androgens, such as testosterone, trigger the development of male characteristics. The secretion of sex hormones is controlled by the hypothalamus and pituitary gland.

SELF-QUIZ

1. Which of the following is *not* true concerning homeostasis?
   a. It is the maintenance of constant internal conditions.
   b. It involves the regulation of body conditions, such as calcium and glucose levels.
   c. It usually prevents major fluctuations in body conditions.
   d. Its maintenance is solely the responsibility of the endocrine system.
2. Unlike most water-soluble hormones, lipid-soluble hormones
   a. usually do not enter target cells.
   b. bind to receptors in the cytoplasm or nucleus of target cells.
   c. cause a cellular response.
   d. are made of amino acids.
3. Explain how the same hormone can have different effects on two different target cells and no effect on a third type of cell.
4. Which of the following controls the activity of all the others?
   a. thyroid gland
   b. hypothalamus
   c. pituitary gland
   d. adrenal cortex
5. Why does the consumption of alcohol lead to frequent urination?
6. A patient comes to a local health clinic with a large swelling in the neck that appears to be goiter. As the physician is taking the patient's history, the patient mentions not having used iodized salt. The patient is overweight and has a slow metabolism. Does this patient have hyperthyroidism or hypothyroidism? How is this problem related to the lack of iodine in the diet?
7. The pancreas increases its output of insulin in response to
   a. an increase in body temperature.
   b. a decrease in blood glucose.
   c. a hormone secreted by the anterior pituitary.
   d. an increase in blood glucose.
8. Your roommate has just been diagnosed as hyperglycemic, which means having an unusually high blood glucose level. Which of the following could be characteristic of this disorder?
   a. Too much insulin is produced after a high-sugar snack.
   b. The hormone glucagon is underactive.
   c. The receptors on cells do not respond to insulin.
   d. any of the above
9. What problems might an athlete have as a result of chronic use of glucocorticoids to manage pain?
10. Testosterone belongs to a class of sex hormones called _____.
11. For each of the following situations, name the hormone that is most likely responsible for the effect described.
    a. While running a marathon, athletes often report that they sense a lot of pain early on. The more they exert themselves, the less pain they report sensing. The hormones involved are _____.
    b. A 9-year-old child has been diagnosed with pituitary dwarfism. The hormone that is lacking is _____.
    c. As part of her treatment for ovarian cancer, a 30-year-old female has both ovaries removed. She begins to notice changes in her skin and breast tissue. These changes are caused by a lack of _____.

Answers to these questions can be found in Appendix: Self-Quiz Answers.

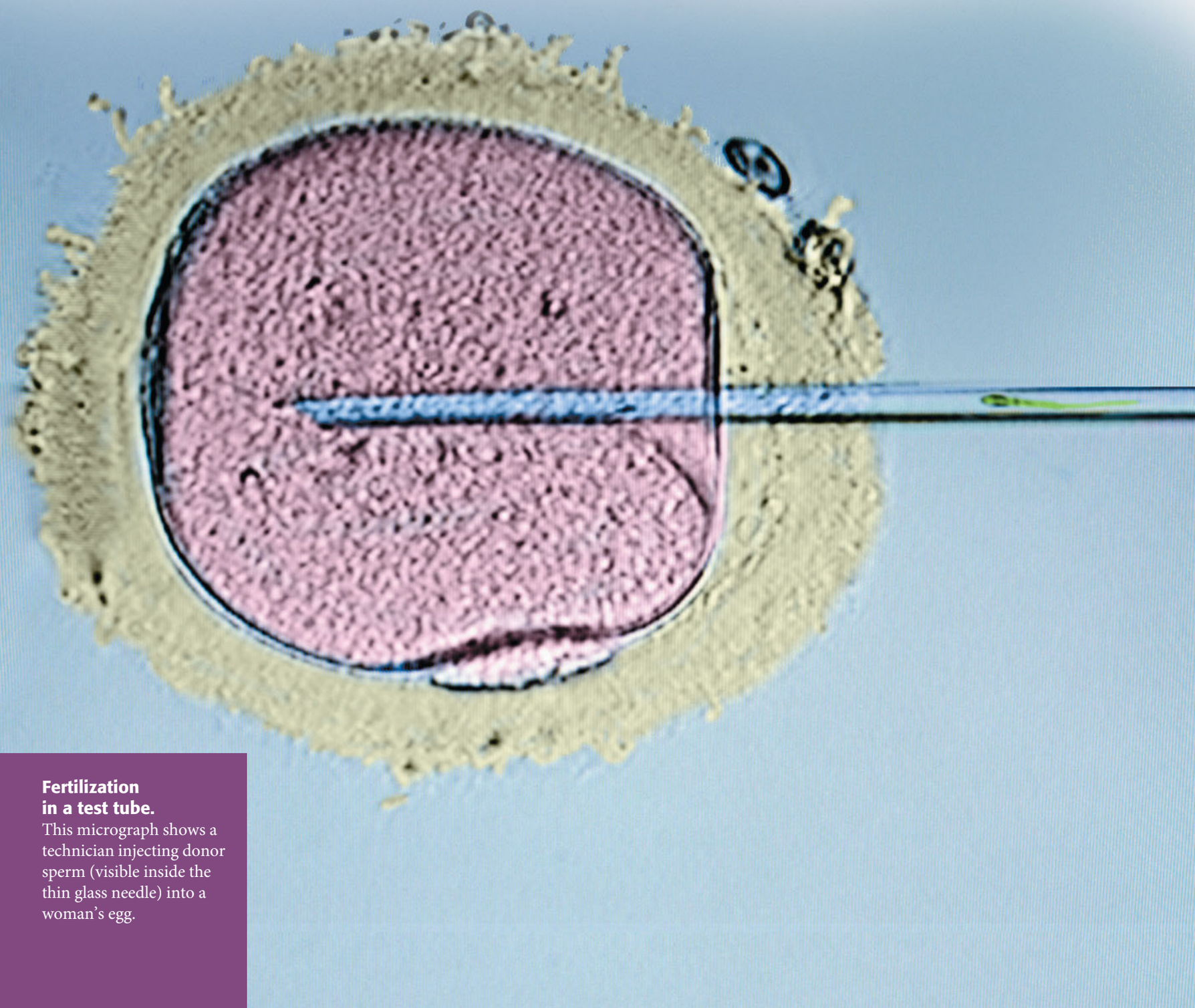
THE PROCESS OF SCIENCE

12. Mice from a genetically modified strain remain healthy as long as they are fed regularly and not allowed to exercise. After they eat, their blood glucose level rises slightly and then declines to a homeostatic level. However, if these mice fast or exercise at all, their blood glucose drops dangerously. Which hypothesis best explains their problem? Explain your choice.
    a. The mice have insulin-dependent diabetes.
    b. The mice lack insulin receptors on their cells.
    c. The mice lack glucagon receptors on their cells.
    d. The mice cannot synthesize glycogen from glucose.

BIOLOGY AND SOCIETY

13. A low rate of secretion of human growth hormone (HGH) causes pituitary dwarfism. Human growth hormone made using recombinant DNA technology enables children who suffer from pituitary dwarfism to grow normally and reach a stature within the normal range. So far, no long-term side effects from HGH used in this way are known. With HGH readily available and relatively inexpensive, some parents who believe that their normal children are not growing fast enough want to use HGH to make them grow faster and taller. Are there reasons to hesitate in treating a normal child with HGH, or are the potential benefits worth the risk? There is some evidence that HGH injected into older adults may delay or even reverse some of the effects of aging. Should HGH be freely available for any adult who wants to use it for that purpose?
14. Type 2 diabetes is becoming increasingly common in the United States. The primary risk factor for type 2 diabetes is a history of obesity. Statistics show that children are becoming obese at an alarmingly high rate, and this correlates with increased rates of type 2 diabetes. When young children become overweight, the problem is usually blamed on nutrition and exercise choices made by the parents. Why do you think today's parents have a harder time feeding their children nutritious meals and providing an exercise program than did parents of previous generations? What can be done to solve this problem? Recently, several families have filed legal action against a fast-food restaurant chain, claiming that their children are obese because they ate there frequently. These parents claim that the restaurant chain is liable because it made the parents think that the food was healthy and would not contribute to obesity. Do you believe that these parents have a case? Explain your response.

26 Reproduction and Development



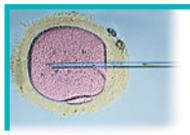
Fertilization in a test tube.
This micrograph shows a technician injecting donor sperm (visible inside the thin glass needle) into a woman's egg.

CHAPTER CONTENTS

Unifying Concepts of Animal Reproduction 552
Human Reproduction 554
Reproductive Health 559
Human Development 562
Reproductive Technologies 568

CHAPTER THREAD
High-Tech Babies

BIOLOGY AND SOCIETY
Life after Death 551
THE PROCESS OF SCIENCE
Can Viable Embryos Be Identified? 569
EVOLUTION CONNECTION
The "Grandmother Hypothesis" 570



High-Tech Babies BIOLOGY AND SOCIETY

Life after Death

Throughout their 18-year marriage, Gary and Francia P. always wanted children. But after multiple miscarriages, the couple came to accept that they were infertile, unable to bear children naturally. Seeking help, they visited a fertility clinic, hoping to use reproductive technologies to fulfill their dream of starting a family.

Two weeks later, Gary died suddenly of a heart attack. At the hospital, six hours after his death, Francia requested that a sample of Gary's sperm be removed. Months later, Francia returned to the fertility clinic. The sample obtained from her husband's body provided just enough sperm for one shot at producing a child. Her eggs were surgically removed and combined with Gary's sperm. The resulting embryos were implanted into Francia's uterus, and one grew into a baby son, Jacob, born about one year after his father's death.

Because of his career as a captain in the Newark, New Jersey, police department, Gary's family was entitled to pension benefits that were tied to the size of his family. After Jacob's birth, Francia applied to the pension board for an increase in her widow's benefits. Should Francia be entitled to this increase? The pension board did not think so, ruling that a child born more than a year after a parent's death is not entitled to benefits from that parent.

Francia appealed in court. There were several previous cases where the courts determined that children born to women who used a deceased husband's sperm had full rights as heirs, but these cases involved men who had donated their sperm before death. Because New Jersey does not have laws governing the rights of children born from sperm obtained after death, Francia's case entered new legal territory. As of late 2011, the outcome was still undetermined.

This case illustrates two important points. First, modern technologies allow us to circumvent the natural course of reproduction in many ways. Second, society's laws have not yet caught up to these new technologies. It is up to all of us to decide what is right in such circumstances. To quote the U.S. Court of Appeals in Philadelphia from a related case, "[We] cannot help but observe that this is, indeed, a new world."

In this chapter, we explore the anatomy and physiology of animal reproduction, paying particular attention to the reproductive structures of humans and how human babies develop from a single cell. Along the way, we'll also consider how modern health practices and technologies circumvent the natural process of sexual reproduction.

Unifying Concepts of Animal Reproduction

Although every individual animal has a relatively short life span, species last much longer because of **reproduction**, the creation of new individuals from existing ones. Animals reproduce in a great variety of ways, but there are two principal modes: asexual reproduction and sexual reproduction.

Asexual Reproduction

Asexual reproduction (reproduction without sex) is the creation of offspring that are genetically identical to a lone parent. Several types of asexual reproduction can be found among animals. Many invertebrates reproduce asexually by **budding**, the outgrowth and eventual splitting off of a new individual from a parent. Hydras, relatives of jellies, reproduce this way **(Figure 26.1)**. The sea anemone shown in **Figure 26.2** is undergoing **fission**, the separation of a parent into two or more offspring of about equal size. Another type of asexual reproduction involves fragmentation, the breaking of the body into several pieces, followed by regeneration, the regrowth of lost body parts. Some organisms have remarkable powers of regeneration. In certain species of sea stars, for example, an arm plus a bit of the central body that has split off can give rise to a new sea star (see Figure 8.1). In some species of sea sponges, if a single sponge is pushed through a wire mesh, each of the resulting clumps of cells can regrow into a new sponge. (These are examples of asexual reproduction as it occurs in nature. Other species have been the target of *artificial* asexual reproduction; see the discussion of cloning in Chapter 11.)

In nature, asexual reproduction has several potential advantages. Because it eliminates the need to find a mate, asexual reproduction allows the individual members of a species to perpetuate themselves even if they are isolated from one another. Asexual reproduction also allows organisms to multiply quickly, without spending time or energy producing sperm and eggs. If an individual is very well suited to its environment, asexual reproduction allows it to reproduce rapidly and exploit available resources.

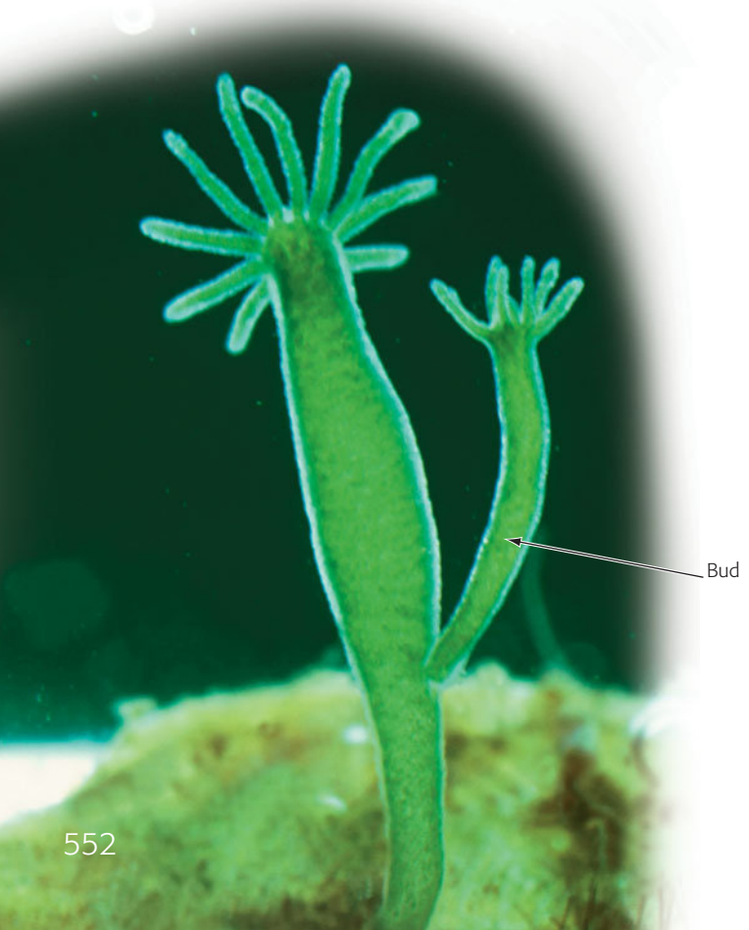
A potential disadvantage of asexual reproduction is that it produces genetically uniform populations. Genetically similar individuals may thrive in a particular environment. But if the environment changes and becomes less favorable to survival (as a result of some natural disaster, say, or a new predator or pathogen), then all individuals may be affected equally, and the entire population may die out. ☑

☑ CHECKPOINT

Name three types of natural asexual reproduction of animals.

Answer: fission, budding, and asexual reproduction involving fragmentation and regeneration

▼ Figure 26.1 Asexual reproduction via budding in a hydra.



▼ Figure 26.2 Asexual reproduction via fission in a sea anemone.



Sexual Reproduction

You know that you have a mix of traits from your mother and father. But you also have a genome distinct from every other human (unless you have an identical twin). You are the product of **sexual reproduction**, creation of offspring by the fusion of two haploid sex cells called **gametes** to form a diploid **zygote**. The male gamete is the **sperm**, and the female gamete is the **egg**. The zygote and the new individual it develops into contain a unique combination of genes carried from the parents via the egg and sperm.

Can you name a multisex animal?

Unlike asexual reproduction, sexual reproduction increases genetic variability among offspring as a result of the huge variety of gametes produced by meiosis (see Chapter 8). Variation is the raw material of evolution by natural selection. When an environment changes, there is a better chance that some of the varying offspring will survive and reproduce than if all the offspring are genetically very similar.

Some animals can reproduce both asexually and sexually, benefiting from both modes. In **Figure 26.3**, you can see two sea anemones of the same species. The one on the left is reproducing asexually (via fission), while the one on the right is releasing eggs. Why would such dual reproductive capabilities be advantageous to an animal? Some animals reproduce asexually when food is ample and conditions are favorable. But when conditions change (becoming colder or drier, for example), these animals switch to sexual reproduction, producing a generation of genetically varied individuals with better potential to adapt to the changing conditions.

Most animals are of a single sex, either male or female. But in some species, each individual is a **hermaphrodite**, meaning that it has both male and female reproductive systems. Some hermaphrodites (such as tapeworms, which can live as parasites in the human intestine) can fertilize their own eggs. Other species require a partner. For example, when earthworms mate, each individual donates and receives sperm.

The mechanics of fertilization play an important part in sexual reproduction. Many aquatic animals use external fertilization, in which the parents discharge their gametes into the water, where fertilization occurs **(Figure 26.4)**. The female and male don't necessarily have to touch to mate. In contrast, nearly all terrestrial animals reproduce when sperm are deposited by a male within the female's body. In the next section, we'll examine the reproductive anatomy that allows one particular terrestrial animal—namely, humans—to achieve sexual reproduction. ☑

☑ CHECKPOINT

What is the most important difference in the genetic makeup of the offspring resulting from sexual versus asexual reproduction?

Answer: *Asexual reproduction produces genetically identical offspring, whereas sexual reproduction produces genetically diverse offspring.*

▼ Figure 26.3 Asexual (left) and sexual (right) reproduction in a starlet sea anemone.



▼ Figure 26.4 External fertilization in frogs. Frogs release eggs and sperm (too small to be seen) into the water, where fertilization takes place. The embrace between the two frogs is a mating ritual that coordinates the simultaneous release of gametes.



Human Reproduction

✓ CHECKPOINT

Arrange the following organs of the male reproductive system in the correct sequence for the travel of sperm: epididymis, testis, urethra, vas deferens.

Answer: testis, epididymis, vas deferens, urethra

Although we tend to focus on the differences between human male and female reproductive systems, there are some important similarities. Both sexes have a pair of **gonads**, the organs that produce gametes. And both sexes have ducts that store and deliver the gametes as well as structures that allow mating. We'll now examine the anatomical features of human reproduction, beginning with the male anatomy.

Male Reproductive Anatomy

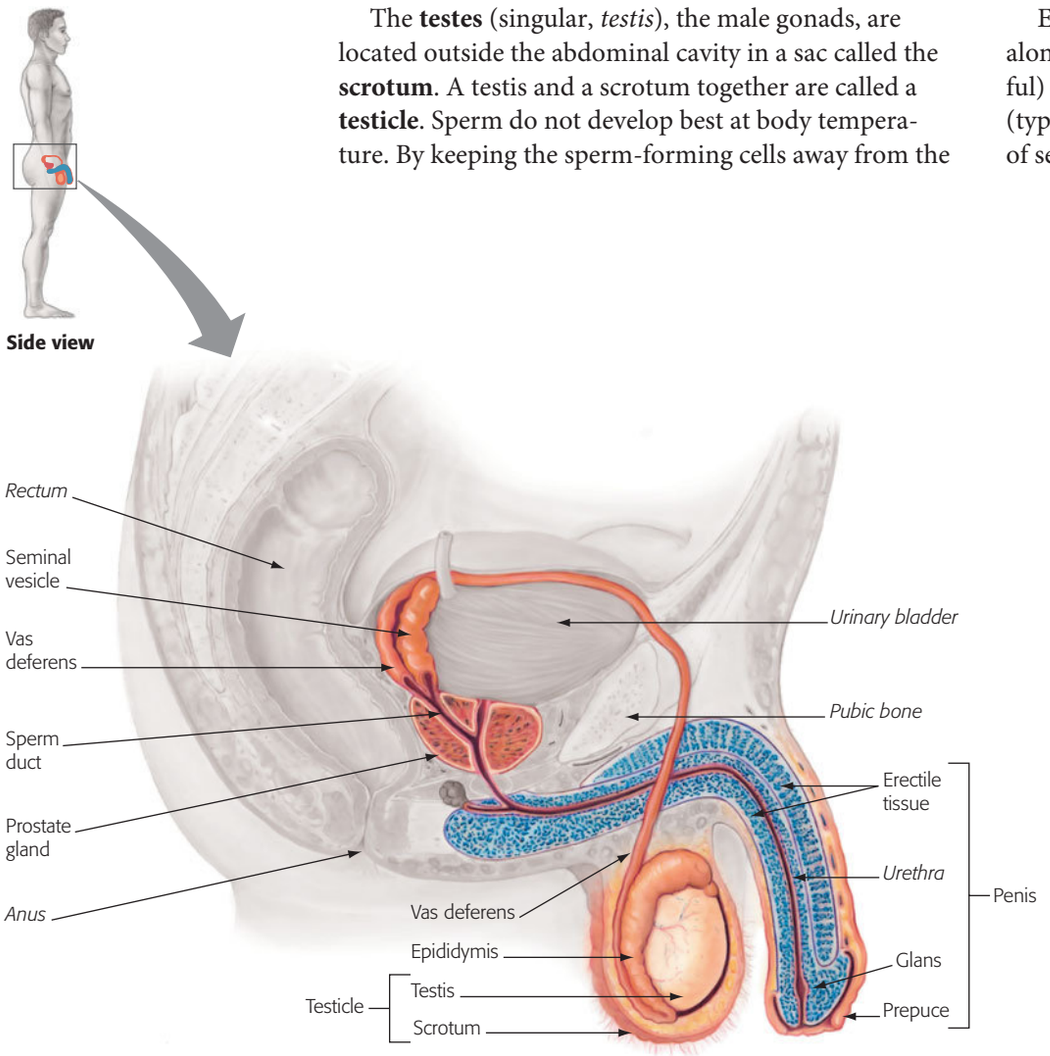
Figure 26.5 presents a side view and a front view of the male reproductive system. The **penis** contains erectile tissue (shown in blue in the figures) that can fill with blood and cause an erection during sexual arousal. The penis consists of a shaft that supports a highly sensitive glans (head). A **prepuce**, or foreskin, covers the glans. The foreskin may be surgically removed, a procedure known as circumcision.

The **testes** (singular, *testis*), the male gonads, are located outside the abdominal cavity in a sac called the **scrotum**. A testis and a scrotum together are called a **testicle**. Sperm do not develop best at body temperature. By keeping the sperm-forming cells away from the body, the scrotum keeps them cool enough to develop normally. In cold conditions, muscles around the scrotum contract, pulling the testes toward the body, maintaining the proper temperature.

From puberty into old age, the testes produce hundreds of millions of sperm each day. From the testes, sperm pass into a coiled tube called the epididymis. During **ejaculation**—expulsion of sperm-containing fluid from the penis—the sperm leave the epididymis and travel through a duct called the **vas deferens** (the target of a vasectomy). The **seminal vesicles** and **prostate gland** add fluid that nourishes the sperm and provides protection from the natural acidity of the vagina. The prostate gland is the source of some of the most common medical problems in men over 40, and prostate cancer is the second most commonly diagnosed cancer in the United States. Each vas deferens, one from each of the two testes, empties into the **urethra**. The urethra conveys, at different times, both sperm and urine out through the penis.

Ejaculation, caused by the contraction of muscles along the sperm ducts, releases about 5 mL (1 teaspoonful) of **semen**. Only 5% of semen consists of sperm (typically 200–500 million of them); the remaining 95% of semen is fluid secreted by the various glands. ✓

▼ Figure 26.5 The male reproductive system. The color blue highlights erectile tissue. Some nonreproductive structures are also labeled (in italics) to help keep you oriented.



Female Reproductive Anatomy

Two views of the female reproductive system are shown in **Figure 26.6**. The outer features of the female reproductive anatomy are collectively called the **vulva**. The **vagina**, or birth canal, opens to the outside just behind the opening of the urethra, the tube through which urine is excreted. An outer pair of thick, fatty ridges, the **labia majora**, protects the entire genital region, and a pair of inner skin folds, the **labia minora**, borders the openings. A thin membrane called the **hymen** partly covers the vaginal opening until sexual intercourse or other vigorous physical activity ruptures it. The **clitoris** is an organ that engorges with blood and becomes erect during sexual arousal. It consists of a short shaft supporting a rounded glans, or head, covered by a small hood of skin called the prepuce. The clitoris has an enormous number of nerve endings and is very sensitive to touch.

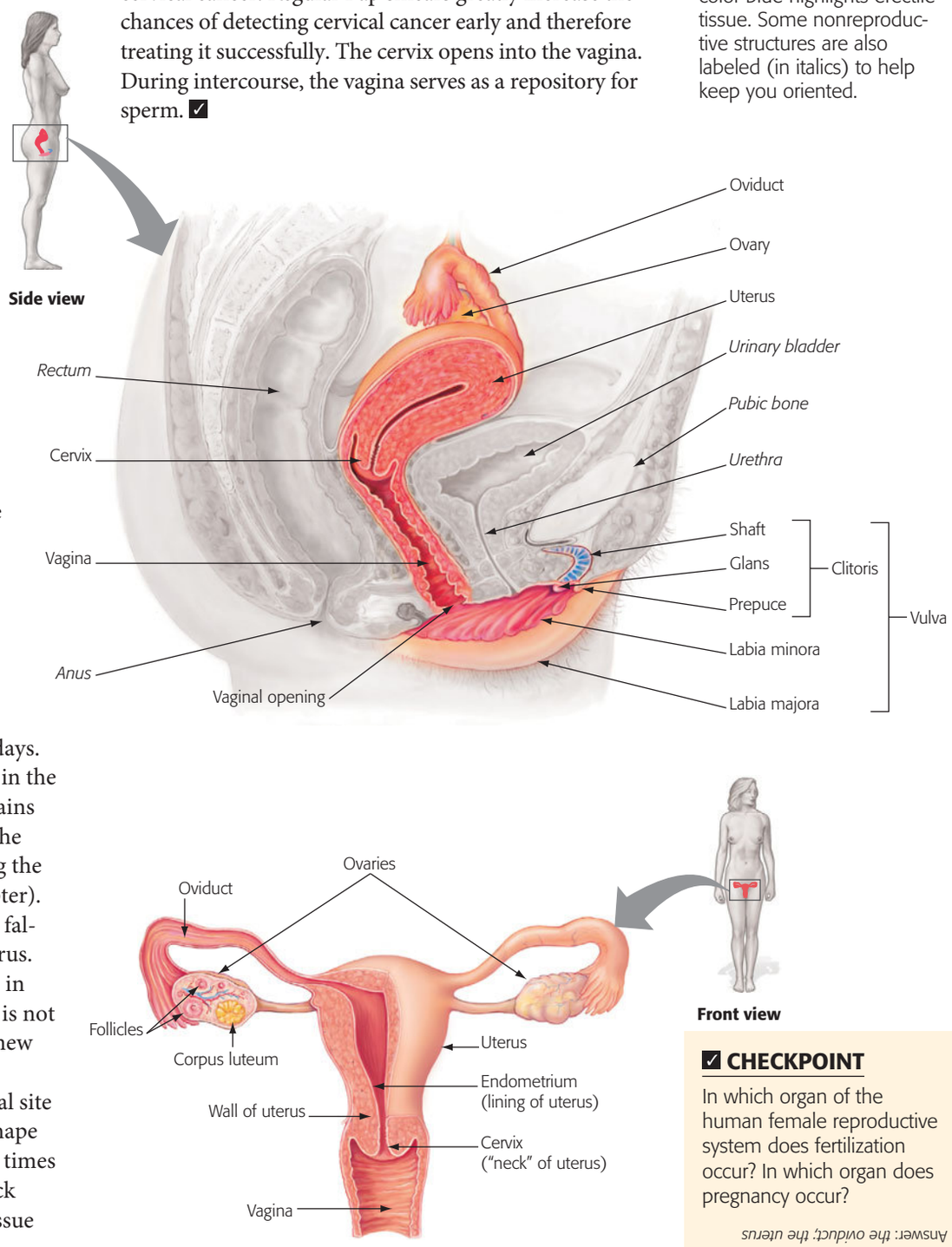
The **ovaries** are the site of gamete production—the gonads—in human females. A woman's ovaries are each about an inch long and have a bumpy surface. The bumps are **follicles**, each consisting of a single developing egg cell surrounded by cells that nourish and protect it. The follicles also produce estrogen, the female sex hormone (see Chapter 25).

A female is born with over a million follicles, but only several hundred will release egg cells during her reproductive years. Starting at puberty and continuing until menopause (the end of fertility, which usually occurs during middle age), one follicle (or rarely two or more) matures and releases its egg cell about every 28 days. An immature egg cell is ejected from the follicle in the process of **ovulation**. After ovulation, what remains of the follicle grows to form a solid mass called the **corpus luteum**, which secretes hormones during the reproductive cycle (as you'll see later in the chapter). The released egg enters an **oviduct** (also called a fallopian tube), where cilia sweep it toward the uterus. If sperm are present, fertilization may take place in the upper part of the oviduct. If the released egg is not fertilized, it is shed during menstruation, and a new follicle matures during the next cycle.

The **uterus** (also called the womb) is the actual site of pregnancy. The uterus is about the size and shape of an upside-down pear, but can grow to several times that size during pregnancy. The uterus has a thick muscular wall lined with a blood-rich layer of tissue called the **endometrium**. An embryo implants in the endometrium and grows there. The term **embryo** is used for the stage in development from the first division of the zygote until body structures begin to appear, about the 9th week. From the 9th week until birth, a developing human is called a **fetus**.

The narrow neck at the bottom of the uterus is the **cervix**. It is recommended that a woman have a yearly Pap test in which cells are removed from around the cervix and examined under a microscope for signs of cervical cancer. Regular Pap smears greatly increase the chances of detecting cervical cancer early and therefore treating it successfully. The cervix opens into the vagina. During intercourse, the vagina serves as a repository for sperm. ☑

▼ Figure 26.6 The female reproductive system. The color blue highlights erectile tissue. Some nonreproductive structures are also labeled (in italics) to help keep you oriented.



☑ CHECKPOINT

In which organ of the human female reproductive system does fertilization occur? In which organ does pregnancy occur?

Answer: the oviduct; the uterus

Gametogenesis

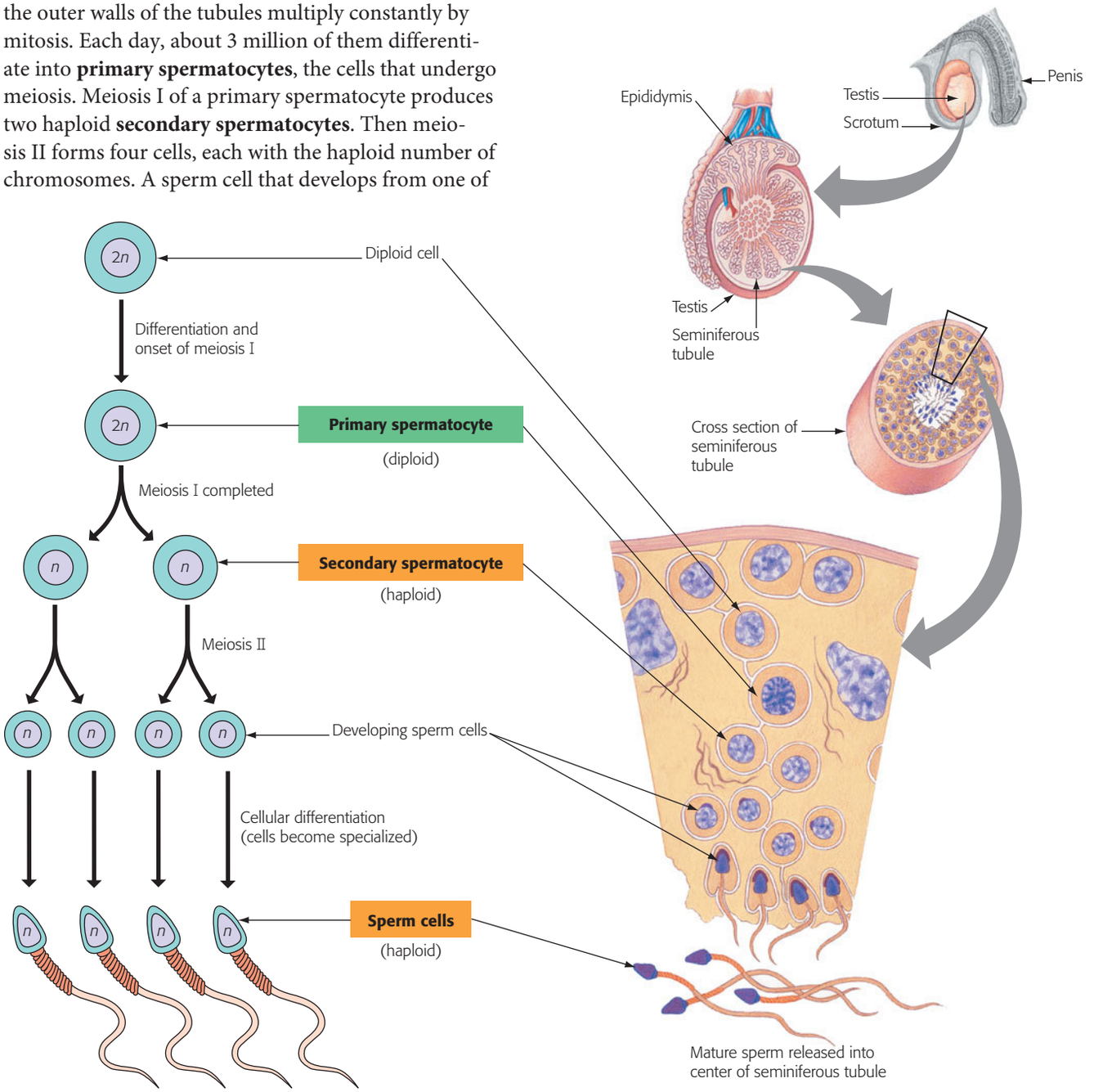
The production of gametes is called **gametogenesis**. Human gametes—sperm and egg—are haploid cells with 23 chromosomes that develop by meiosis from diploid cells with 46 chromosomes. (You may find it helpful to review the discussion of meiosis in Chapter 8, particularly Figures 8.13–8.15.) There are significant differences in gametogenesis between human males and females, so we'll examine the processes separately.

Spermatogenesis

The formation of sperm cells is called **spermatogenesis** (Figure 26.7). Sperm cells develop inside the testes in coiled tubes called the **seminiferous tubules**. Cells near the outer walls of the tubules multiply constantly by mitosis. Each day, about 3 million of them differentiate into **primary spermatocytes**, the cells that undergo meiosis. Meiosis I of a primary spermatocyte produces two haploid **secondary spermatocytes**. Then meiosis II forms four cells, each with the haploid number of chromosomes. A sperm cell that develops from one of these haploid cells is gradually pushed toward the center of the seminiferous tubule. From there, it passes into the epididymis, where it matures, becomes motile, and is stored until ejaculation. Because the pre-sperm cells continuously replenish themselves, there is a never-ending supply of spermatocytes, allowing males to produce sperm throughout their adult lives.

Oogenesis

Figure 26.8 summarizes **oogenesis**, the development of mature egg cells, also called ova (singular, *ovum*). At birth, each ovary contains many thousands of follicles. Each follicle contains a single dormant **primary oocyte**, a diploid cell that has paused its cell cycle in prophase of meiosis I.

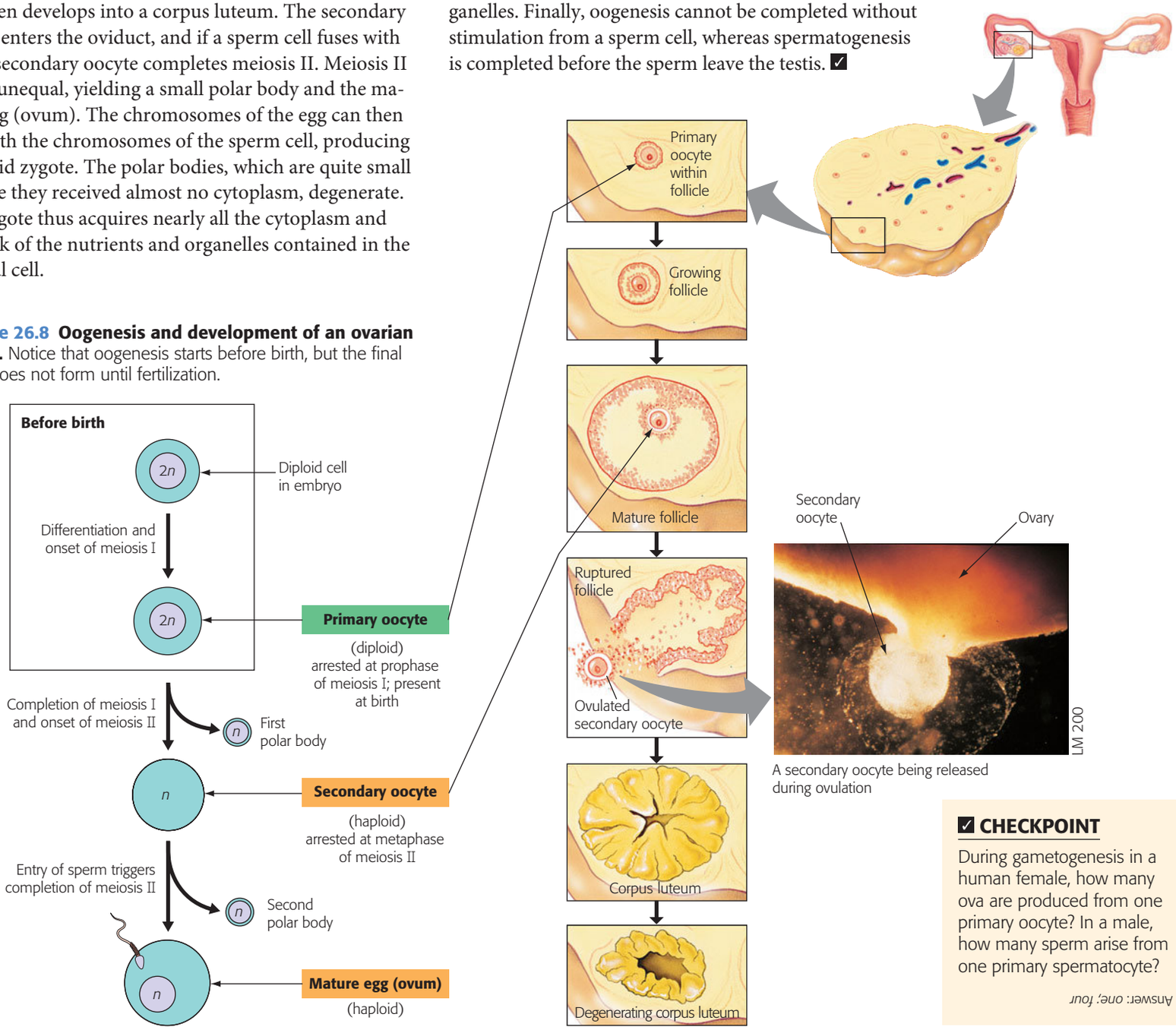


► **Figure 26.7 Spermatogenesis.** This process takes about 65–75 days in the human male.

A primary oocyte can be triggered to develop further by the hormone FSH (follicle-stimulating hormone). After puberty and until menopause, about every 28 days, FSH from the pituitary gland stimulates one of the dormant follicles to develop. The follicle enlarges, and the primary oocyte within it completes meiosis I and begins meiosis II. The division of the cytoplasm in meiosis I is unequal, with a single **secondary oocyte** receiving almost all of it. The smaller of the two daughter cells, called the first polar body, receives almost no cytoplasm.

About the time the secondary oocyte forms, the pituitary gland secretes LH (luteinizing hormone), which triggers ovulation. The ripening follicle bursts, releasing its secondary oocyte from the ovary. The ruptured follicle then develops into a corpus luteum. The secondary oocyte enters the oviduct, and if a sperm cell fuses with it, the secondary oocyte completes meiosis II. Meiosis II is also unequal, yielding a small polar body and the mature egg (ovum). The chromosomes of the egg can then fuse with the chromosomes of the sperm cell, producing a diploid zygote. The polar bodies, which are quite small because they received almost no cytoplasm, degenerate. The zygote thus acquires nearly all the cytoplasm and the bulk of the nutrients and organelles contained in the original cell.

Both oogenesis and spermatogenesis produce haploid gametes, but there are several important differences between the two processes. One obvious difference is location: testes in the male and ovaries in the female. Furthermore, human males create new sperm every day from puberty through old age. Human females, on the other hand, create primary oocytes only during their fetal development. Another difference is that four gametes result from each diploid parent cell during spermatogenesis, whereas oogenesis results in only one gamete from each parent cell. Moreover, there are significant differences in the cells produced by meiosis: Sperm are small and motile and contain relatively few nutrients; eggs are large, nonmotile, and well stocked with nutrients and organelles. Finally, oogenesis cannot be completed without stimulation from a sperm cell, whereas spermatogenesis is completed before the sperm leave the testis. ☑



▼ Figure 26.8 Oogenesis and development of an ovarian follicle. Notice that oogenesis starts before birth, but the final ovum does not form until fertilization.

A secondary oocyte being released during ovulation

☑ CHECKPOINT

During gametogenesis in a human female, how many ova are produced from one primary oocyte? In a male, how many sperm arise from one primary spermatocyte?

Answer: one; four

The Female Reproductive Cycle

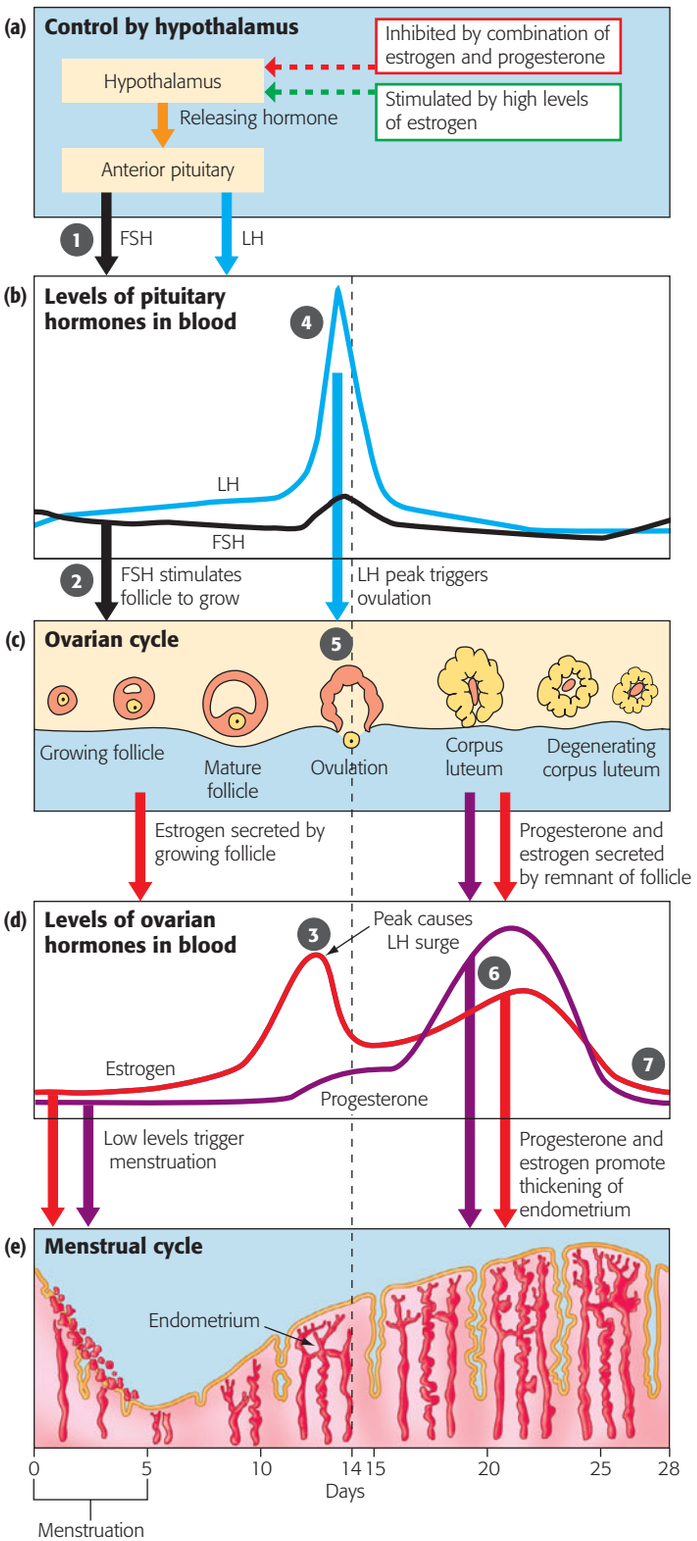
Human females have a **reproductive cycle**, a recurring series of events that produces gametes, makes them available for fertilization, and prepares the body for pregnancy (Figure 26.9). The reproductive cycle repeats every 28 days, on average, but cycles from 20 to 40 days are not uncommon. The reproductive cycle is actually two cycles in one. The **ovarian cycle** (see Figure 26.9c) controls the growth and release of an egg. During the **menstrual cycle** (see Figure 26.9e), the uterus is prepared for possible implantation of an embryo. Hormonal messages coordinate the two cycles.

By convention, the first day of a woman's "period" is designated day 1 of the menstrual cycle. **Menstruation** is uterine bleeding caused by the breakdown of the endometrium, the blood-rich inner lining of the uterus. If an embryo implants in the uterine wall, it will obtain nutrients from the endometrium, and the thickened lining will not be discharged. Menstruation is thus a sign that pregnancy has not occurred during the previous cycle. Menstruation usually lasts 3–5 days. The menstrual discharge, which leaves the body through the vagina, consists of blood, clusters of cells, and mucus. After menstruation, the endometrium regrows, reaching its maximum thickness in 20–25 days.

The hormones shown in parts (a), (b), and (d) of Figure 26.9 regulate the ovarian and menstrual cycles, synchronizing ovulation with preparation of the uterus for possible implantation of an embryo. At the start of the ovarian cycle, the hypothalamus secretes a releasing hormone that stimulates the anterior pituitary gland to ❶ increase its output of FSH (follicle-stimulating hormone) and LH (luteinizing hormone). True to its name, FSH ❷ stimulates the growth of an ovarian follicle. As the maturing follicle grows, it secretes estrogen in increasing amounts. After about 12 days, ❸ estrogen levels peak, which causes ❹ a sudden surge of FSH and LH. This stimulates ovulation, and ❺ the developing follicle within the ovary bursts and releases its egg. Ovulation takes place on day 14 of the typical 28-day cycle.

Besides promoting rupture of the follicle, the sudden surge of LH has several other effects. It stimulates the completion of meiosis I, transforming the primary oocyte in the follicle into a secondary oocyte (see Figure 26.8). LH also promotes the secretion of estrogen and progesterone by the corpus luteum. Estrogen and progesterone regulate the menstrual cycle. Rising levels of these two hormones ❻ promote thickening of the endometrium. The combination of estrogen and progesterone also

Figure 26.9 The reproductive cycle of the human female. This figure shows how (c) the ovarian cycle and (e) the menstrual cycle are regulated by changing hormonal levels, represented in parts (a), (b), and (d). The time scale at the bottom of the figure applies to parts (b)–(e).



inhibits further secretion of FSH and LH, ensuring that a second follicle does not mature during this cycle. Further degeneration of the corpus luteum causes the levels of estrogen and progesterone to fall off. Once these hormones (7) fall below a critical level, the endometrium begins to shed, starting menstruation on day 1 of the next cycle. Now that estrogen and progesterone are no longer there to inhibit it, the pituitary secretes FSH and LH, and a new cycle begins.

The description of the reproductive cycle in this section assumes that fertilization has not occurred. If it does, the embryo implants into the endometrium and secretes a hormone called HCG (human chorionic gonadotropin). HCG maintains the corpus luteum, which continues to secrete progesterone and estrogen, keeping the endometrium intact. As you will see later, some forms of contraception work by mimicking the high levels of hormones that occur during pregnancy. Most home pregnancy tests work by detecting HCG in the urine. In males, HCG boosts testosterone production, so its use is banned by many sports organizations. In 2009, baseball slugger Manny Ramirez was suspended from baseball for 50 games after testing positive for HCG. ☑

☑ CHECKPOINT

What hormonal changes trigger the start of menstruation?

Answer: decreasing levels of estrogen and progesterone

Reproductive Health

Now that you've read about the anatomy and physiology of the human reproductive system, you can apply this knowledge to two issues of reproductive health: contraception and the transmission of disease.

Contraception

Contraception is the deliberate prevention of pregnancy. There are many forms of contraception that interfere with different steps in the process of becoming pregnant. Table 26.1 lists the most common methods of birth control and their failure rates when used correctly and when used typically. Note that these two rates are often quite different, emphasizing the importance of learning to use contraception correctly.

Complete abstinence (avoiding intercourse) is the only totally effective method of contraception, but other methods are effective to varying degrees. Sterilization, surgery that prevents sperm from reaching an egg, is very reliable. A woman may have a **tubal ligation** (have her "tubes tied"). In this procedure, a doctor removes a short section from each oviduct, often tying (ligating) the remaining ends and thereby blocking the route of sperm to egg. A man may have a **vasectomy**, in which a doctor cuts a section out of each vas deferens to prevent sperm from reaching the urethra. Both forms of sterilization are free from side effects and relatively safe. They are meant to be permanent but can sometimes be surgically reversed. Although such reversals are becoming increasingly successful, they carry some risk of damaging the ducts.

What forms of contraception are most reliable?

The effectiveness of other methods of contraception depends on how they are used. Temporary abstinence, also called the **rhythm method** or **natural family planning**, depends on refraining from intercourse during the days around ovulation, when fertilization is most likely. In theory, the time of ovulation can be determined by monitoring changes in body temperature and the composition of cervical mucus, but careful monitoring and record keeping are required. Additionally, the length of the reproductive

Table 26.1 Contraceptive Methods

	Pregnancies per 100 Women per Year	
Method	**Used Correctly**	**Typically**
None		85
Birth control pill	0.1	5
Vasectomy	0.1	0.15
Tubal ligation	0.2	0.5
Rhythm method	1–9	20
Withdrawal	4	19
Condom (male)	3	14
Diaphragm and spermicide	6	20
Spermicide alone	6	26

cycle can vary from month to month, and sperm can survive for 3–5 days within the female reproductive tract, making natural family planning among the most unreliable methods of contraception in actual practice. Withdrawal of the penis from the vagina before ejaculation is also ineffective, because sperm may exit the penis before climax.

If used correctly, barrier methods can be quite effective at physically preventing the union of sperm and egg. **Condoms** are sheaths, usually made of latex, that fit over the penis or within the vagina. A **diaphragm** is a dome-shaped rubber cap that covers the cervix. It requires a doctor's visit for proper fitting. To be more effective, barrier devices (including condoms) can be used in combination with **spermicides**, sperm-killing chemicals in the form of a jelly, cream, or foam; spermicides used alone are not reliable.

Some of the most effective methods of contraception prevent the release of gametes. Oral contraceptives, or **birth control pills**, come in several different forms that contain varying formulations of a synthetic estrogen and/or a synthetic progesterone. Steady intake of these hormones simulates their constant levels during pregnancy. In response to being "fooled" that pregnancy has occurred, the hypothalamus fails to send the signals that start development of an ovarian follicle. Ovulation ceases, preventing pregnancy. In addition to pills, various combinations of these hormones are also available as a shot (Depo-Provera), a ring inserted into the vagina, or a skin patch **(Figure 26.10)**. Some of these contraceptives maintain hormone levels for up to 3 months, so a user will have only four periods a year. Currently, there is no chemical contraceptive available that can prevent the production or release of sperm.

▼ Figure 26.10 A contraceptive skin patch containing birth control hormones.



Certain drugs can prevent fertilization or implantation even after intercourse has occurred. Birth control pills can be prescribed in high doses for emergency contraception, also called **morning-after pills (MAPs)**. If taken within 3 days of intercourse, morning-after pills are about 75% effective at preventing pregnancy. Such treatments should only be used in emergency situations because they have significant side effects. In 2006, the Food and Drug Administration approved the sale of morning-after pills (the "Plan B" brand) without a prescription. If pregnancy has occurred, the drug RU-486 (mifepristone) can induce an abortion, the termination of a pregnancy in process. RU-486 must be taken within the first 7 weeks of pregnancy and requires a doctor's prescription and several visits to a medical facility.

Responsible sex involves more than preventing unwanted pregnancies. It also involves preventing the spread of sexually transmitted diseases, the focus of the next section. ☑

☑ CHECKPOINT

What methods of contraception are foolproof or nearly so?

Answer: abstinence and sterilization (vasectomy and tubal ligation)

Sexually Transmitted Diseases

Sexually transmitted diseases (STDs) are contagious diseases spread by sexual contact. **Table 26.2** lists the STDs most common in the United States, organized by the type of infectious agent. Notice that bacteria, viruses, protists, and fungi can all cause STDs.

The most common bacterial STD (with nearly a million new cases reported annually in the United States and over 90 million worldwide) is **chlamydia**. In fact, chlamydia and gonorrhea are the two most frequently reported infectious diseases in the United States. Chlamydia poses a public health challenge because it is frequently "silent"—often producing no visible symptoms. The primary symptoms are genital discharge and a burning sensation during urination, but half of infected men and three-quarters of infected women do not notice any symptoms. Long-term complications are rare among men, but up to 40% of infected women develop pelvic inflammatory disease (PID). The inflammation associated with PID may block the oviducts or scar the uterus, causing infertility. Fortunately, chlamydia can be easily treated with a single dose of an antibiotic. But early screening is required to catch the disease before any scarring occurs. Sexually active women are encouraged to be screened for chlamydia and other STDs annually.

In contrast to bacterial STDs, viral STDs are not curable. They can be controlled by medications, but

symptoms and the ability to infect others remain a possibility throughout a person's lifetime. One in five Americans is infected with **genital herpes**, caused by the herpes simplex virus type 2, a variant of the virus that causes cold sores. Most outbreaks heal within a few weeks, but the virus lies dormant within nearby nerve cells. Months or years later, it can reemerge, causing fresh sores that allow the virus to be spread to sexual partners. Abstinence during outbreaks, the use of condoms, and the use of antiviral medications that minimize symptoms can reduce the spread of herpes. But there is no cure, so infection lasts a lifetime.

Which STDs last a lifetime?

AIDS, caused by HIV (discussed in Chapters 10 and 24), poses one of the greatest health challenges in the world today, particularly among the developing nations of Africa and Asia. But even within the United States, there are 56,000 new infections each year, one-third of which result from heterosexual contact.

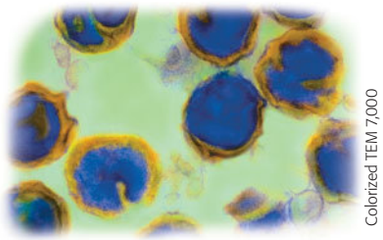
Another sexually transmitted virus is the human papillomavirus (HPV). There are many known strains of HPV, some of which cause genital warts. Furthermore, HPV infection causes nearly all cases of cervical cancer. A vaccine against HPV is available, but it is only effective before infection. Therefore, it is recommended that a woman be vaccinated (a series of three shots) before she becomes sexually active.

Anyone who is sexually active should have regular medical exams, be tested for STDs, and seek immediate help if any suspicious symptoms appear—even if they are mild. STDs are most prevalent among teenagers and young adults; nearly two-thirds of infections occur among people under 25. The best way to avoid the spread of STDs is, of course, abstinence. Alternatively, latex condoms provide the best protection for "safe sex." ✓

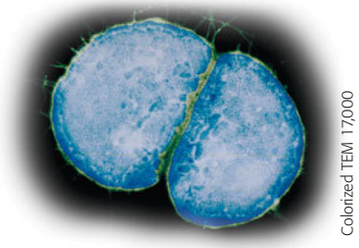
✓ CHECKPOINT

What is the most important difference between STDs caused by viruses and STDs caused by bacteria in terms of their treatment?

Answer: Bacterial STDs can be cured with antibiotics; viral STDs are permanent.


Colorized TEM 7,000

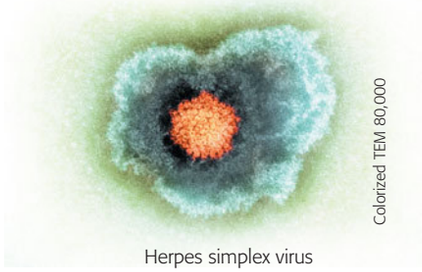
Chlamydia trachomatis


Colorized TEM 17,000

Neisseria gonorrhoeae


Colorized SEM 4,000

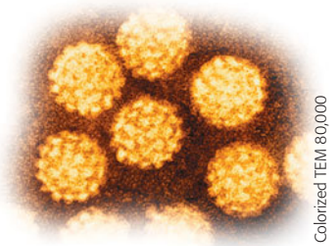
Treponema pallidum


Colorized TEM 80,000

Herpes simplex virus

Table 26.2 STDs Common in the United States

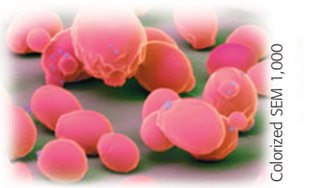
Disease	Microbial Agent	Major Symptoms and Effects	Treatment
Bacterial			
Chlamydial infections	*Chlamydia trachomatis*	Genital discharge, itching, and/or painful urination; often no symptoms in women; pelvic inflammatory disease (PID)	Antibiotics
Gonorrhea	*Neisseria gonorrhoeae*	Genital discharge; painful urination; sometimes no symptoms in women; PID	Antibiotics
Syphilis	*Treponema pallidum*	Ulcer (chancre) on genitalia in early stages; spreads throughout body and can be fatal if not treated	Antibiotics can cure in early stages
Viral			
Genital herpes	Herpes simplex virus type 2, occasionally type 1	Recurring symptoms: small blisters on genitalia, painful urination, skin inflammation; linked to cervical cancer, miscarriage, birth defects	The drug valacyclovir can prevent recurrences
Genital warts	Human papillomaviruses (HPV), multiple types	Painless growths on genitalia; HPV can cause cervical cancer	Removal by freezing, vaccine
AIDS and HIV infection	HIV	See Chapter 24	Combination of drugs
Protistan			
Trichomoniasis	*Trichomonas vaginalis*	Vaginal irritation, itching, and discharge; usually no symptoms in men	Antiprotist drugs
Fungal			
Candidiasis (yeast infections)	*Candida albicans*	Similar to symptoms of trichomoniasis; frequently acquired nonsexually	Antifungal drugs


Colorized TEM 80,000

Papillomaviruses


Colorized SEM 2,200

Trichomonas vaginalis


Colorized SEM 1,000

Candida albicans

Human Development

Embryonic development begins with **fertilization**, or conception, the union of a sperm and egg to form a zygote. In this section, we will examine the process of fertilization and the subsequent development of a human.

Fertilization

Sexual intercourse releases hundreds of millions of sperm into the vagina, but only a few thousand sperm survive the several-hour trip to the egg in the oviduct. Of these sperm, only a single one can enter and fertilize the egg. All the other millions of sperm die.

Repeating a theme we've seen again and again during our exploration of anatomy, the shape of sperm is related to what they do (form fits function). A mature human sperm has a streamlined shape that enables it to swim through fluids in the vagina, uterus, and oviduct (Figure 26.11). The sperm's head contains a haploid nucleus and is tipped with a membrane-enclosed sac called the acrosome. The middle of the sperm contains mitochondria that use high-energy nutrients from the semen, especially the sugar fructose, to fuel movement of the flagellum.

▼ **Figure 26.11 A human sperm cell.**

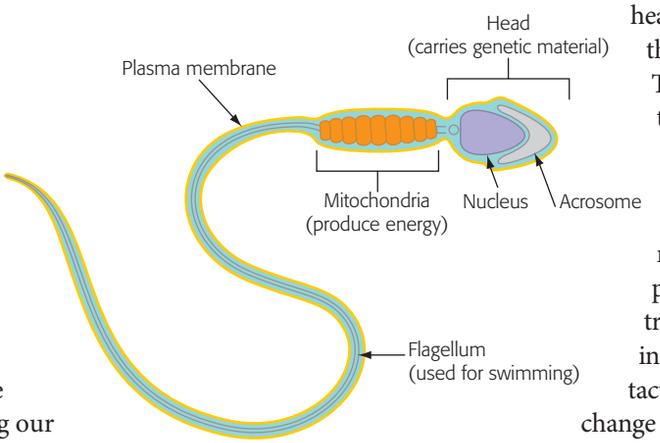
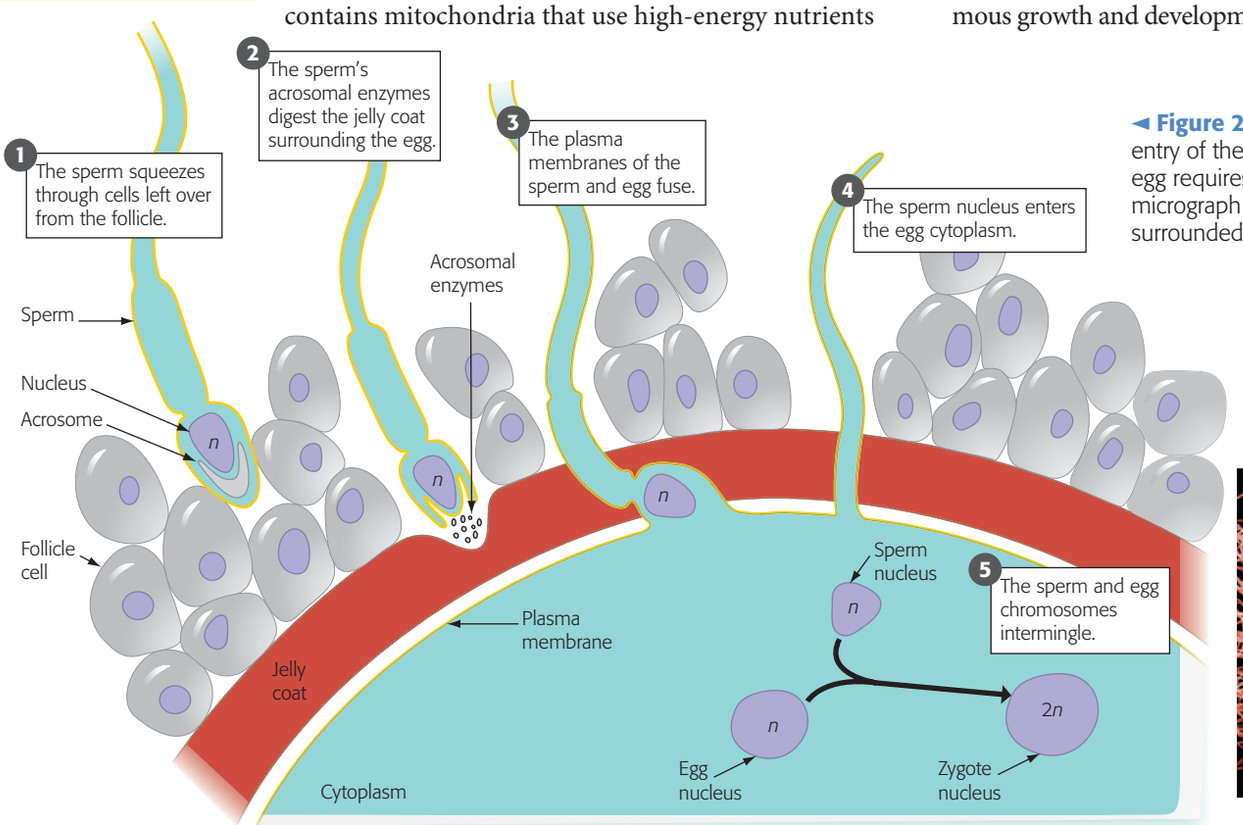


Figure 26.12 traces one sperm through the events of fertilization. The sperm (1) approaches and then (2) contacts the jelly coat (red) that surrounds the egg. The acrosome in the sperm's head releases a cloud of enzymes that digest a hole in the jelly. This hole allows the sperm head to (3) fuse its plasma membrane with that of the egg. Fusion of the two membranes makes it possible for the sperm nucleus to (4) enter the cytoplasm of the egg. Fusion also triggers completion of meiosis II in the egg. Furthermore, contact of sperm with egg triggers a change in the egg's plasma membrane that makes it impenetrable to other sperm cells. This blockage of other sperm ensures that the zygote that is forming contains only the diploid number of chromosomes. The chromosomes of the egg and sperm nuclei (5) are eventually enclosed in a single diploid nucleus. In the diploid zygote, the egg's metabolic machinery awakens from dormancy and gears up in preparation for the enormous growth and development that will soon follow. ✓

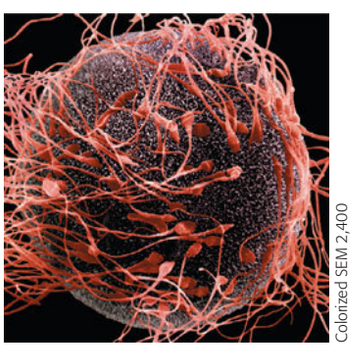
✓ CHECKPOINT

What is the function of a sperm's acrosome?

Answer: It releases enzymes that dissolve the outer layer of the egg, allowing the sperm to penetrate.



◄ **Figure 26.12 Fertilization.** The entry of the sperm nucleus into the egg requires several steps. The electron micrograph (below) shows a human egg surrounded by sperm.



Colorized SEM 2,400

Basic Concepts of Embryonic Development

A single-celled human zygote formed by fertilization is smaller than the period at the end of this sentence. From this humble start, the zygote develops into a full-fledged organism with trillions of cells organized into complex tissues and organs. Clearly, this process requires an astonishing amount of cell division and specialization. The key to development in all organisms is that each stage takes place in a highly organized fashion.

How are twins formed?

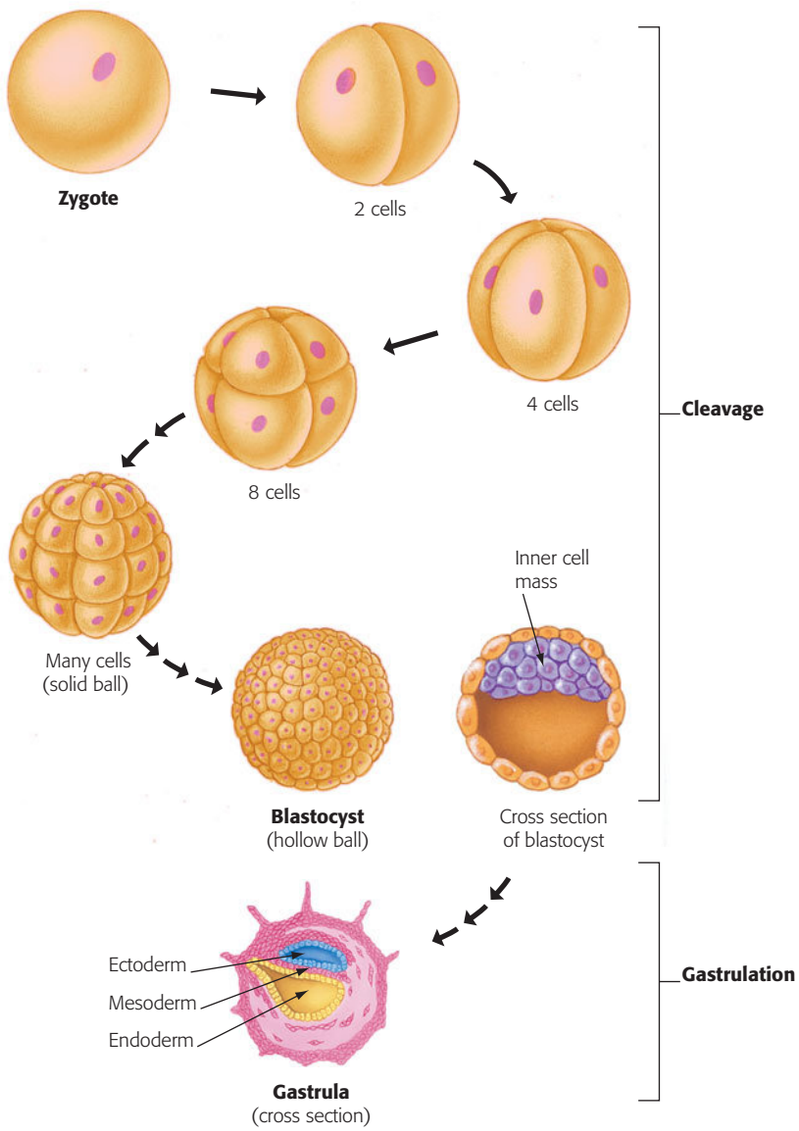
Development begins with **cleavage**, a series of rapid cell divisions that produces a multicellular ball. After the zygote divides for the first time, about 36 hours after fertilization, it is called an embryo. Rarely, and apparently at random, the two cells of the early embryo separate from each other. When this separation happens, each cell may "reset" and act as a zygote; the result is the development of identical (monozygotic) twins. (Nonidentical, or dizygotic, twins result from a completely different mechanism: Two separate eggs fuse with two separate sperm to produce two genetically unique zygotes that develop at the same time.)

During cleavage, DNA replication, mitosis, and cytokinesis occur rapidly, but the total amount of cytoplasm remains unchanged. As a result, the overall size of the embryo does not change; instead, each cell division partitions the embryo into twice as many smaller cells, each with its own nucleus **(Figure 26.13)**. Cleavage continues as the embryo moves down the oviduct toward the uterus. A central cavity begins to form in the embryo. About 6–7 days after fertilization, the embryo has reached the uterus as a fluid-filled hollow ball of about 100 cells called a blastocyst. Protruding into the central cavity on one side of the human blastocyst is a small clump of cells called the inner cell mass, which will eventually form the fetus. Occasionally, an embryo does not travel down the oviduct to the uterus. The result is an ectopic pregnancy, one in which the embryo develops in the wrong location. Ectopic pregnancies are invariably fatal to the embryo and can be dangerous to the mother, requiring immediate medical attention.

The second stage of development, under way by 9 days after conception, is **gastrulation** (see the bottom of Figure 26.13). The cells of the early embryo begin an organized migration that produces the **gastrula**, an embryo with three main layers. The three layers produced in gastrulation are embryonic tissues called ectoderm, endoderm, and mesoderm. The ectoderm eventually develops into the nervous system and outer layer of skin (epidermis). The endoderm becomes the innermost lining of the digestive system and organs such as the liver, pancreas, and thyroid. The mesoderm gives rise to most other organs and tissues, such as the heart, kidneys, and muscles.

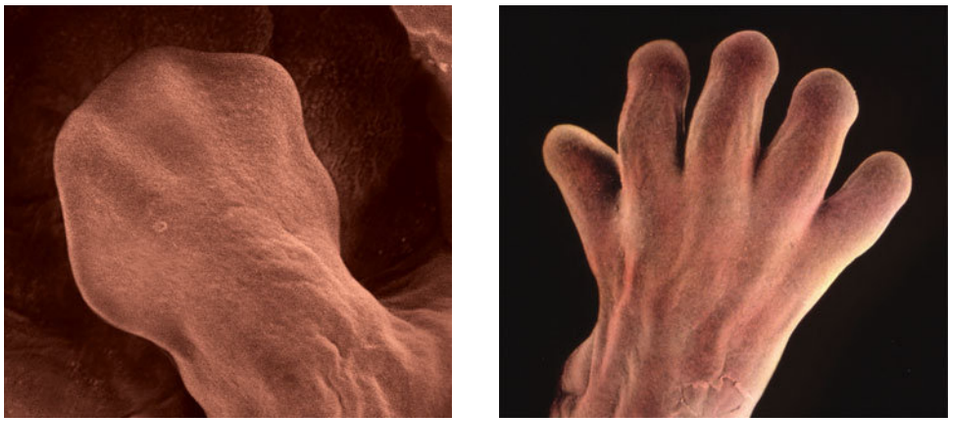
At this stage, various cellular changes contribute to the formation of embryonic structures. All developmental processes depend on chemical signals passed between neighboring cells and cell layers, telling embryonic cells precisely what to do and when. The mechanism by which one group of cells influences the development of an adjacent group of cells is called **induction**. Its effect is to switch on a set of genes whose expression makes the receiving cells differentiate into a specific cell or tissue type. For example, inductive signals can cause cells to change shape or to migrate from one location to another within the developing embryo. Another key

▼ Figure 26.13 Early development of an embryo. Notice that each round of division during cleavage does not change the total size of the embryo. Instead, there are more cells, and each cell is smaller.



developmental process is **programmed cell death**, which kills selected cells. For example, some genes encode proteins that kill certain cells in developing human hands and feet, separating the fingers and toes **(Figure 26.14)**.

During the course of embryonic development, a sequence of chemical signals between cells leads to increasingly greater specialization as organs begin to take shape. The importance of these processes is underscored by birth defects that result from improper signaling. Spina bifida is a condition that results from the failure of a tube of ectoderm cells to properly close and form the spine during the first month of fetal development. Infants born with spina bifida often have permanent nerve damage that results in paralysis of the lower limbs. ☑



◄ Figure 26.14
Programmed cell death in a developing human hand.
Proteins produced during human development destroy cells in the early hand (left), creating the spaces between fingers (right).

☑ CHECKPOINT

Place these steps of development in order: organ formation, fertilization, gastrulation, cleavage.

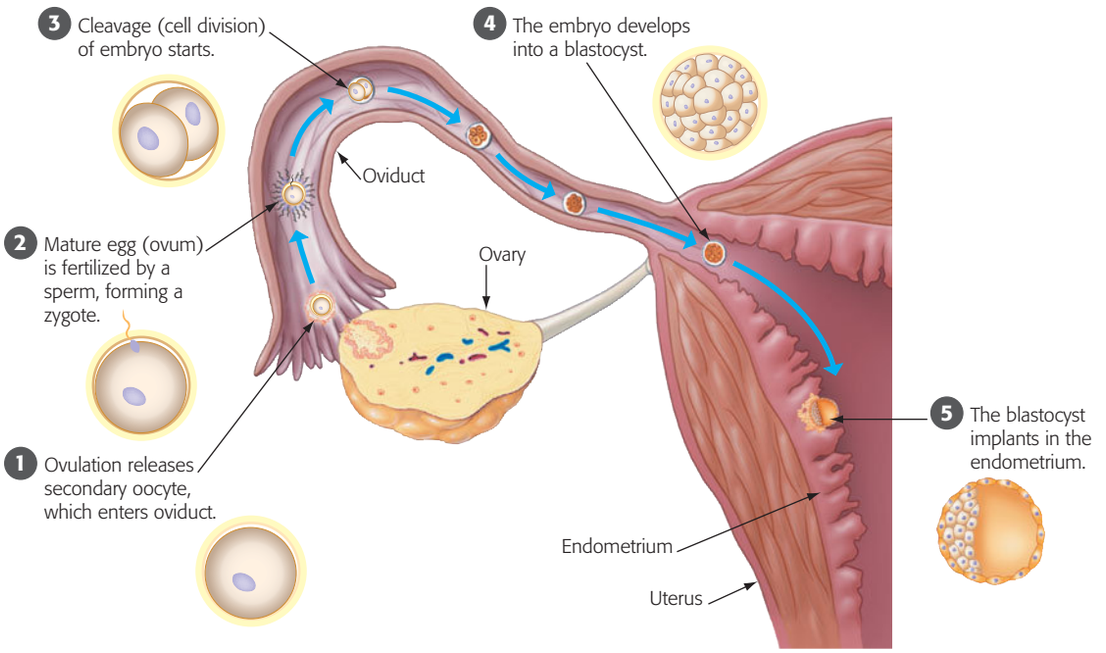
Answer: fertilization, cleavage, gastrulation, organ formation

Pregnancy and Early Development

Pregnancy, or **gestation**, is the carrying of developing young within the female reproductive tract. It begins at fertilization and continues until birth. In humans, gestation lasts about 266 days (38 weeks) from fertilization, but is usually measured as 40 weeks (9 months) from the start of the last menstrual cycle. Other mammals have much shorter or longer gestation periods (3 weeks in mice, 22 months in elephants).

What animal stays pregnant for nearly two years?

The early stages in human development are summarized in **Figure 26.15**. Fertilization and cleavage take place in the oviduct. About a week after conception, the embryo reaches the uterus and implants itself into the



► Figure 26.15
Early stages of human development.
Fertilization takes place in the oviduct. As the zygote travels down the oviduct, cleavage starts. By the time the embryo reaches the uterus, it has become a blastocyst, and it implants into the endometrial lining.

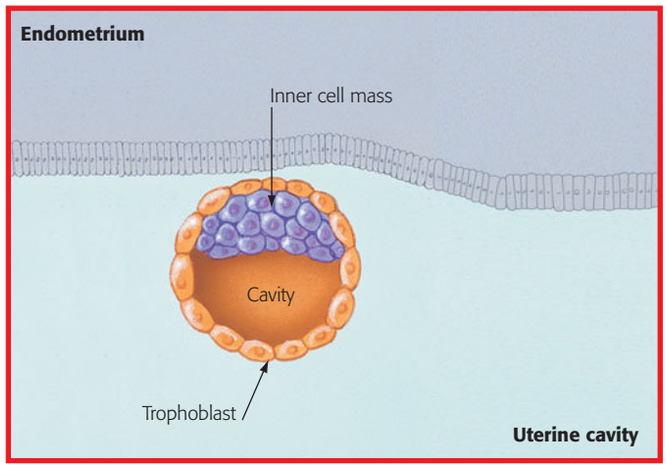
endometrium. By this time, the embryo has become a blastocyst, with a central fluid-filled cavity and an inner cell mass (Figure 26.16a). These early embryonic cells are **stem cells**, with the potential to give rise to every type of cell in the body. (As discussed in Chapter 11, embryonic stem cells have great potential as medical tools.) The outer cell layer, called the **trophoblast** (Figure 26.16b), becomes part of the **placenta**, the organ that provides nourishment and oxygen to the embryo and helps dispose of its wastes.

Figure 26.16c shows the embryo about a month after conception. Besides the growing embryo, there are now several pieces of life-support equipment: the amnion, the yolk sac, the allantois, and the chorion. The amnion is a fluid-filled sac that encloses and protects the embryo. The amnion usually breaks just before childbirth, and the amniotic fluid leaves the mother's body through her vagina. Many anxious couples are startled when her "water breaks," and take this as a sign to get to the hospital. The yolk sac produces the embryo's first blood cells and its first gamete-forming cells in the gonads. The allantois forms part of the **umbilical cord**—the lifeline between the embryo and the placenta. The outermost membrane, the **chorion**, becomes part of the placenta.

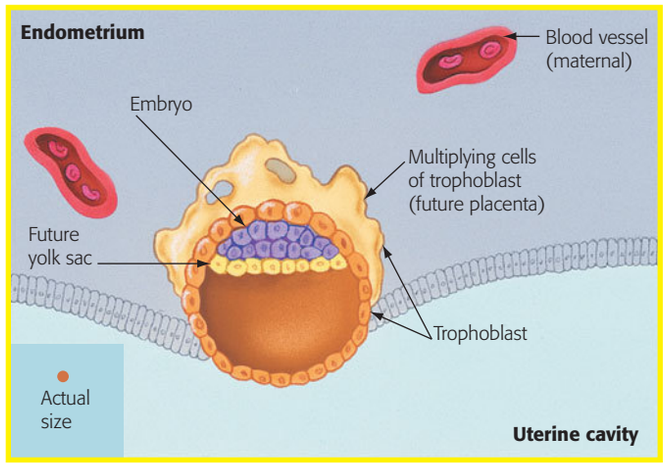
The placenta develops **chorionic villi**, finger-like outgrowths containing embryonic blood vessels. These blood vessels are closely associated with blood vessels of the mother's endometrium. The chorionic villi absorb nutrients and oxygen from the mother's blood via diffusion and pass these substances to the embryo. The villi also diffuse wastes from the embryo to the mother's bloodstream. Although substances can pass back and forth via diffusion, the fetus has its own blood supply that does not mix with the mother's. As discussed in Chapter 9, a small sample of chorionic villus tissue can be removed for prenatal genetic testing.

The placenta provides for other needs of the embryo as well. For example, it allows protective antibodies to pass from the mother to the fetus. However, chemicals in tobacco smoke, alcohol, and other drugs can also cross the placenta, and these harmful substances can cause developmental abnormalities and raise the chances of miscarriage. Additionally, viruses—the German measles virus and HIV, for example—can cross the placenta and cause disease. ☑

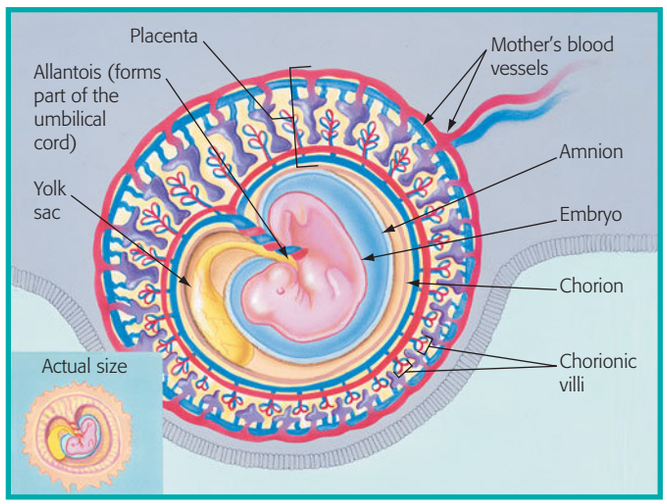
Figure 26.16 A human embryo: the first month.



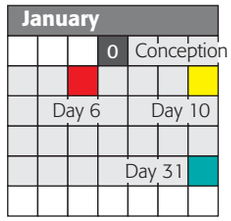
(a) Day 6: Before implantation. By 6 days after conception, the embryo has developed into a blastocyst.



(b) Day 10: Implantation under way. After implantation, the inner cell mass of embryonic stem cells will develop into the fetus. The outer layer of trophoblast cells will become the embryo's contribution to the placenta.



(c) Day 31: The embryo and its life-support equipment



☑ CHECKPOINT

Why should a woman who is trying to get pregnant avoid drugs such as alcohol and nicotine?

Answer: Drugs can pass to the developing embryo from the mother's bloodstream and affect it before the mother even knows she is pregnant.

The Stages of Pregnancy

In this section, we use the series of photographs in **Figure 26.17** to illustrate the rest of human development as it takes place in the uterus. For convenience, we divide pregnancy (the period from conception to birth) into three **trimesters** of about 3 months each.

The First Trimester

The first photograph in Figure 26.17 shows a human embryo about 5 weeks after fertilization. In that brief time, a single cell has developed into a highly organized multicellular embryo about 7 mm (0.28 inch) long. Its brain and spinal cord have begun to take shape. It also has four stumpy limb buds, a short tail, and primitive gill-like structures. Overall, a month-old human embryo looks pretty much like a month-old embryo of any other vertebrate species (see Figure 13.10).

When did you have structures similar to gills and a tail?

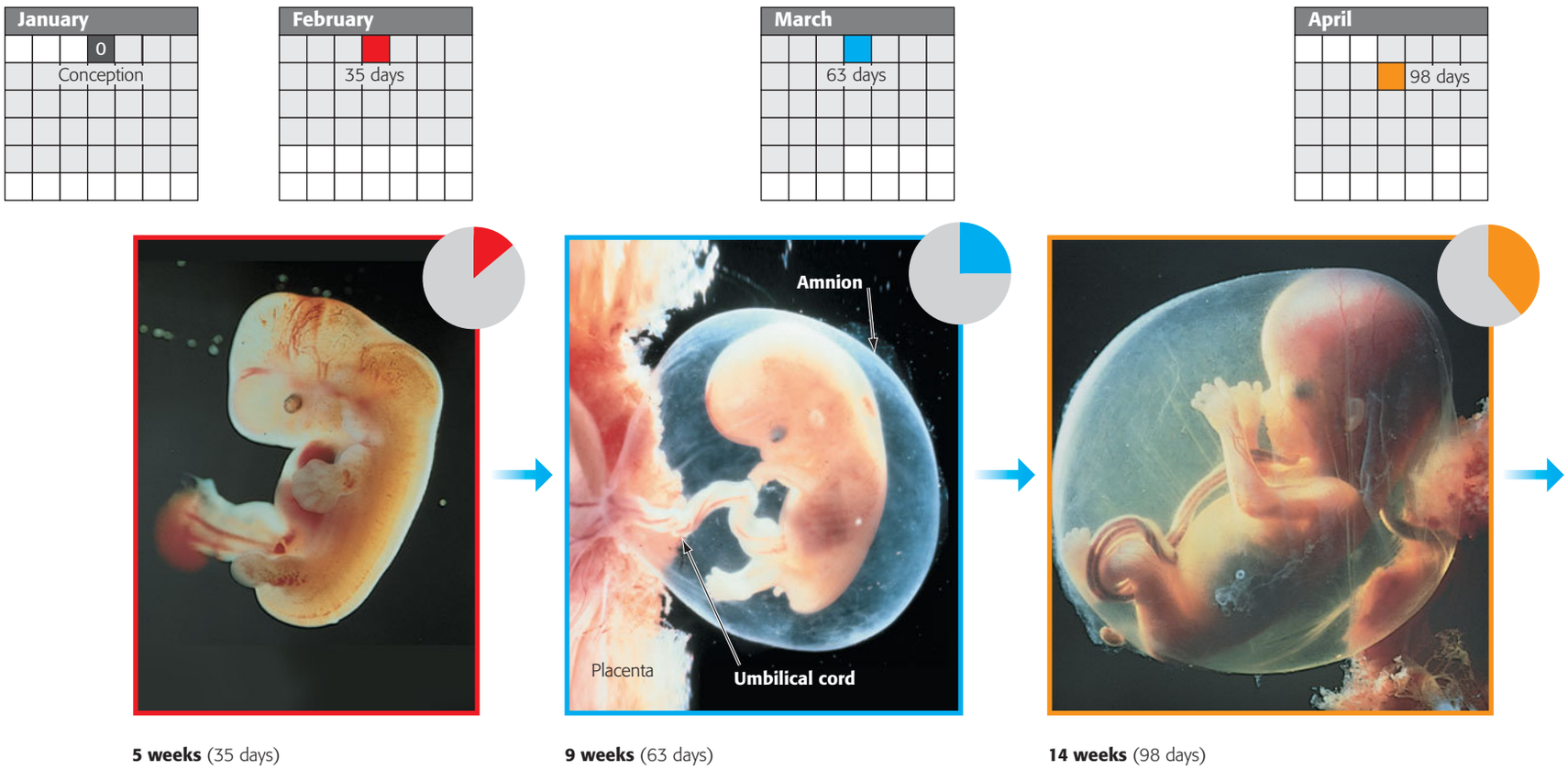
The next photograph shows a developing human, now called a fetus, about 9 weeks after fertilization. The large pinkish structure on the left is the placenta, which is attached to the fetus by the umbilical cord. The clear sac around the fetus is the amnion. The fetus is about 5.5 cm (2.2 inches) long and has all of its organs and major body parts, including muscles and the bones of the back and ribs. The limb buds have become tiny arms and legs with fingers and toes. By the end of the first trimester, the fetus looks like a miniature human being, albeit one with an oversized head. By this time, the sex of the fetus can be determined by an ultrasound exam **(Figure 26.18)**.

The Second Trimester

The main developmental changes during the second and third trimesters involve an increase in size and general refinement of the human features—nothing as dramatic as the changes of the first trimester. A 14-week-old fetus is about 6 cm (2.4 inches) long.

At 20 weeks, well into the second trimester, the fetus is about 19 cm (7.6 inches) long, weighs about half a kilogram (1 pound), and has the face of an infant, complete with eyebrows and eyelashes. Its arms, legs, fingers, and toes have lengthened. It also has fingernails and toenails and is covered with fine hair. By this time, the fetal heartbeat is detectable with a stethoscope, and the mother can usually feel the fetus moving. Because of the limited space in the uterus, the fetus flexes forward into the so-called fetal position, with its head tucked against

▼ Figure 26.17 The development of a human.



5 weeks (35 days)

9 weeks (63 days)

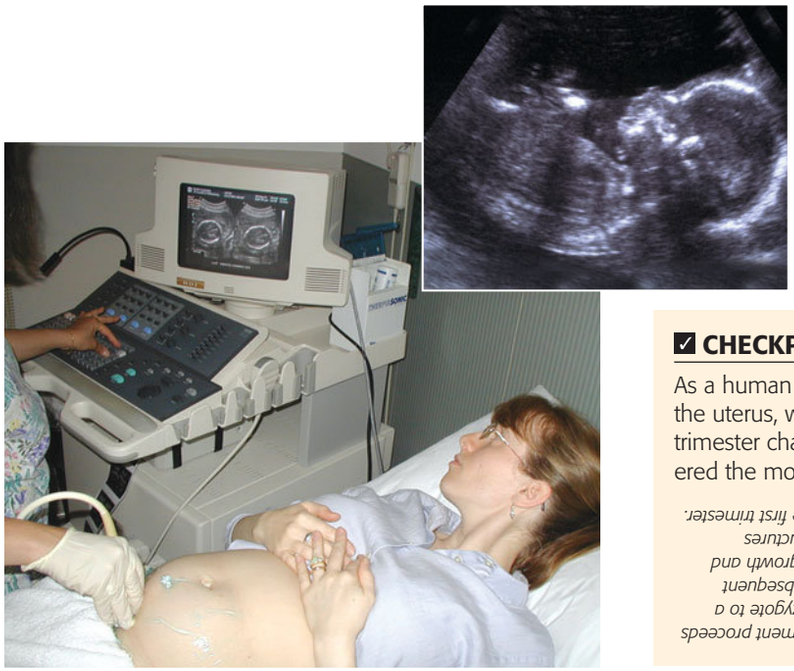
14 weeks (98 days)

its knees. By the end of the second trimester, the fetus's eyes are open, its teeth are forming, and its bones have begun to harden.

The Third Trimester

The third trimester is a time of rapid growth as the fetus gains the strength it will need to survive outside the protective environment of the uterus. Babies born prematurely—as early as 24 weeks—may survive, but they require special medical care after birth. During the third trimester, the fetus's circulatory and respiratory systems undergo changes that will allow the switch to air breathing. The fetus begins to gain the ability to maintain its own temperature, and its muscles thicken. It also loses much of its fine body hair, except on its head. The fetus usually rotates so that its head points down toward the cervix, and it becomes less active as it fills the space in the uterus. As the fetus grows and the uterus expands around it, the mother's abdominal organs may be squeezed, causing frequent urination, digestive troubles, and backaches. At birth, babies average about 50 cm (20 inches) in length and weigh 3–4 kg (6–8 pounds). ☑

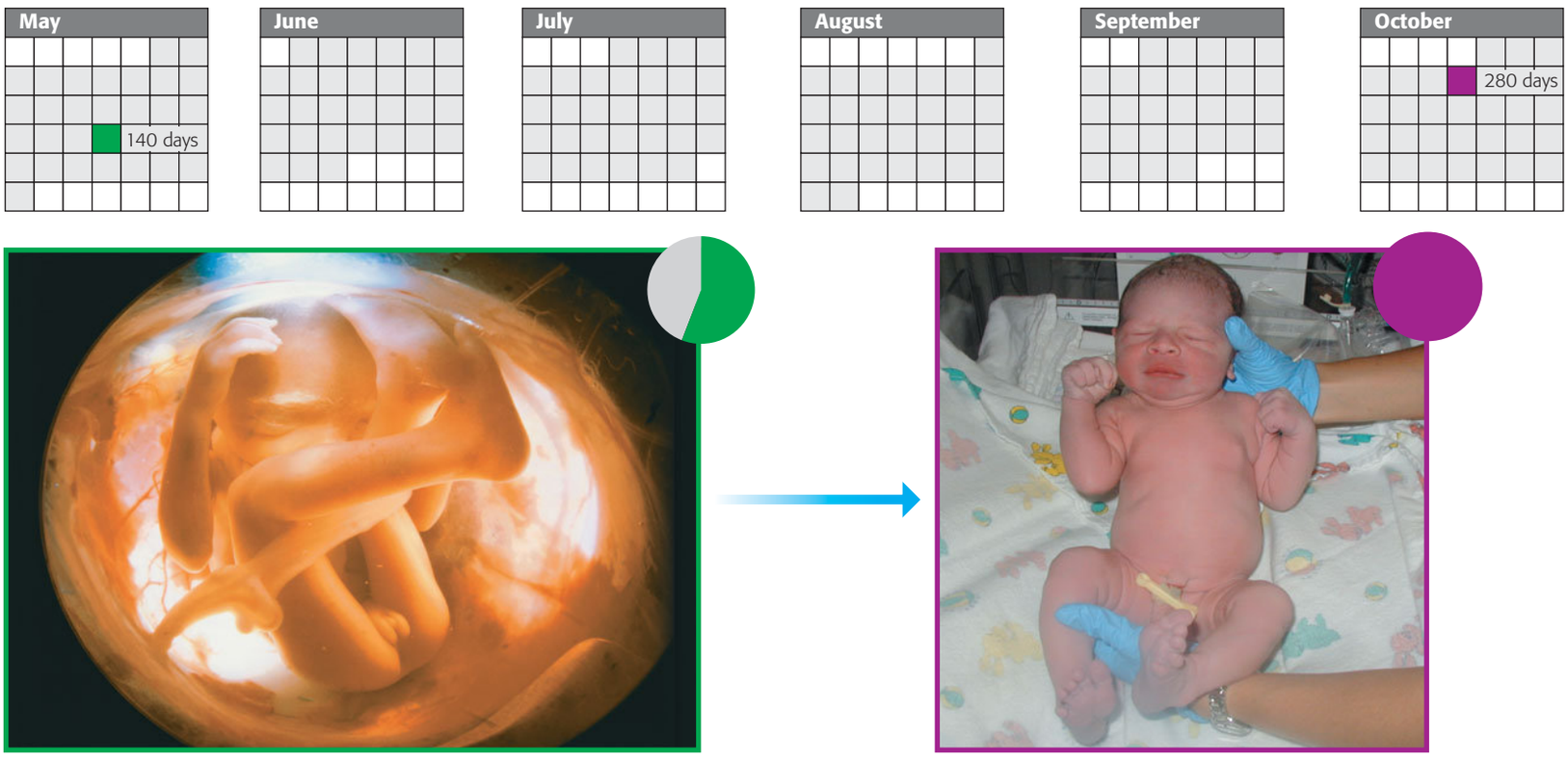
▼ **Figure 26.18** **Ultrasound imaging.** An ultrasound image is produced when high-frequency sounds from an ultrasound scanner held against a pregnant woman's abdomen bounce off the fetus. The inset image shows a fetus in the uterus at about 18 weeks.



☑ CHECKPOINT

As a human develops in the uterus, why are the first-trimester changes considered the most dramatic?

Answer: The development proceeds from a single-celled zygote to a miniature human. Subsequent changes are mainly growth and refinement of the structures developed during the first trimester.



20 weeks (140 days)

At birth (280 days)

Childbirth

The birth of a child is brought about by **labor**, a series of strong, rhythmic contractions of the uterus. Several hormones bring about labor. One of the most important is oxytocin, a hormone produced by the fetus's cells and, late in pregnancy, the mother's pituitary gland. Oxytocin stimulates muscles in the uterus to contract. Uterine contractions stimulate the release of more oxytocin, which in turn increases the contractions—an example of positive-feedback control. The result is climactic—the intense muscle contractions that propel a baby from the womb. If a mother is overdue, or if labor has continued for a long time, a doctor may inject oxytocin to promote a more rapid birth.

Figure 26.19 shows the three stages of labor. (1) The first stage, dilation, is the time from the onset of labor until the cervix dilates, or opens, to a width of about 10 cm (about 4 inches). Dilation is the longest stage of labor, typically lasting 6–12 hours, sometimes considerably longer. (2) The period from full dilation of the cervix to delivery of the infant is called the expulsion stage. Strong uterine contractions, lasting about 1 minute each, occur every 2–3 minutes, and the mother feels an increasing urge to push with her abdominal muscles. Within a period of 20 minutes to an hour or so, the infant is forced down and out of the uterus and vagina. After the baby is born, the umbilical cord is clamped and cut. The stump of the cord remains for several weeks, then shrivels and falls off, leaving the belly button. (3) The final stage is the delivery of the placenta ("afterbirth"), usually within 15 minutes after the birth of the baby.

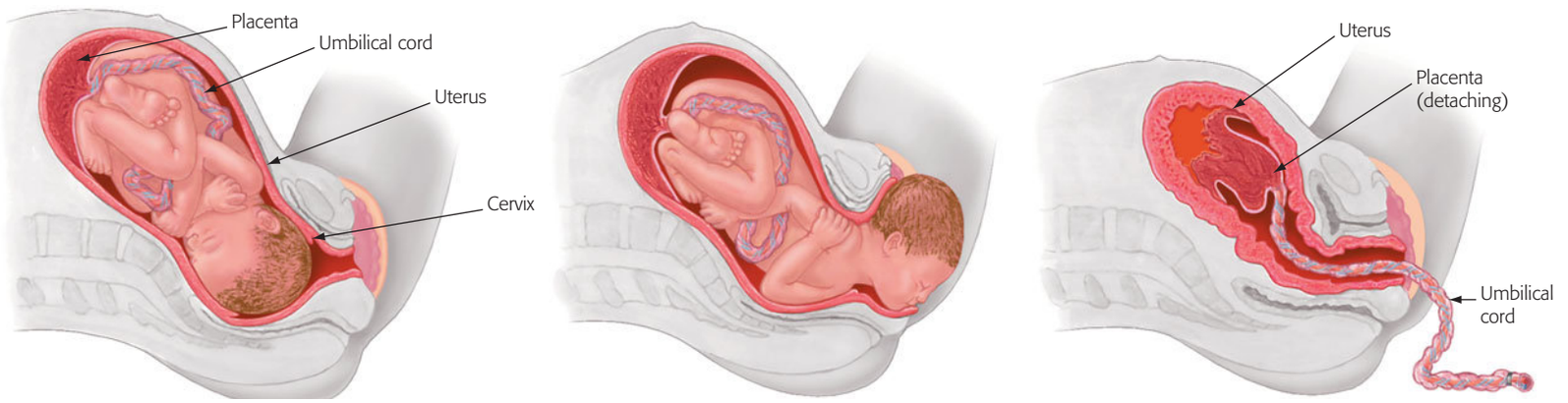
Hormones continue to be important after birth. Decreasing levels of progesterone and estrogen allow the uterus to start returning to its prepregnancy state. The pituitary hormone prolactin promotes milk production (called lactation) by the mammary glands. At first, a yellowish antibody-rich fluid called colostrum is secreted. After 2–3 days, normal milk production begins. ✓

✓ CHECKPOINT

The onset of labor is marked by the dilation of the _____.

Answer: cervix

▼ Figure 26.19 The three stages of labor.



(1) **Dilation of the cervix** (2) **Expulsion: delivery of the infant** (3) **Delivery of the placenta**

Reproductive Technologies

In previous sections, we examined the normal means of human sexual reproduction. Many couples, however, are unable to conceive children because of one or more abnormalities. Today, reproductive technologies can solve many of these problems.

Infertility

About 15% of couples who want children are unable to conceive, even after a year of regular, unprotected sex. Such a condition is called **infertility**, and it can have many causes.

In most cases, infertility can be traced to problems with the man. His testes may not produce enough sperm (a "low sperm count"), or the sperm may not be vigorous enough to reach an egg. In other cases, infertility is caused by **impotence**, also called erectile dysfunction, the inability to maintain an erection. Temporary impotence can result from alcohol or drug use or from psychological problems. Permanent impotence can result from nervous system or circulatory problems.

Female infertility can result from a lack of eggs, a failure to ovulate, or blocked oviducts (often due to scarring resulting from a sexually transmitted disease).

Other women are able to conceive but cannot support a growing embryo in the uterus. The resulting multiple miscarriages can take a heavy emotional toll.

There are reproductive technologies that can help many cases of infertility. For a low sperm count, there is often a simple solution. Underproduction of sperm is frequently caused by a man's scrotum being too warm, so a switch of underwear from briefs (which hold the scrotum close to the body) to boxers may help. If that doesn't work, sperm can be collected, concentrated, and then injected into the woman's uterus via the vagina. Drug therapies (such as Viagra) and penile implants can treat impotence. If a man produces no functioning sperm, the couple may elect to use another man's sperm from a sperm bank.

If a woman has normal eggs that are not being released properly, hormone injections can induce ovulation; such treatments frequently result in multiple pregnancies (twins, triplets, or more). If a woman has no eggs of her own, they can be obtained from a donor for fertilization and injection into the uterus. Although sperm can be collected without any danger to the donor, the collection of eggs is a surgical procedure that involves pain and risk for the donating woman. For this reason, egg "donors" are typically paid for their time and discomfort.

If a woman cannot maintain pregnancy, she and her partner may enter into a legal contract with a surrogate mother who agrees to carry the couple's child to birth. This method has worked for many couples, but serious ethical and legal problems can arise if a surrogate mother changes her mind and wants to keep the baby she has carried. A number of states have laws restricting surrogate motherhood. ☑

☑ CHECKPOINT

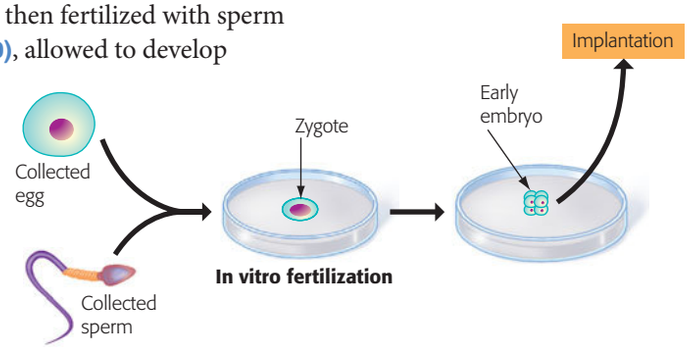
What is the difference between infertility and impotence?

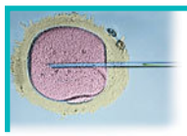
Answer: Infertility is the inability to produce offspring; impotence is the inability to maintain an erection.

In Vitro Fertilization

A procedure performed in vitro ("in glass") happens under artificial laboratory conditions rather than within the living body (in vivo). **In vitro fertilization (IVF)**—sometimes called the creation of a "test-tube baby"—begins with the administration of drugs that promote the development of multiple eggs (instead of the one egg that typically occurs during each ovulation). The eggs are surgically removed and then fertilized with sperm in a petri dish **(Figure 26.20)**, allowed to develop for several days, and then injected into a woman's uterus. There, one or more embryos may successfully implant and continue development. The sperm and eggs, as well as the embryos created, can be used immediately or frozen for later use.

▼ Figure 26.20 In vitro fertilization.





High-Tech Babies THE PROCESS OF SCIENCE

Can Viable Embryos Be Identified?

In vitro fertilization typically involves the creation of many embryos. Because the procedure is so expensive, it would be helpful to identify those embryos with the greatest chance of success.

To address this need, some European researchers started with the **observation** that cells can be removed from the outer layer of a preimplantation blastocyst without harming the embryo. The researchers formed the **hypothesis** that analyzing the gene activity within such cells could provide useful information about the chances of a successful pregnancy from the embryo. Their **prediction** was that gene expression would differ between successful and unsuccessful embryos.

Their **experiment** involved a combination of several procedures that you have learned about in previous chapters. The participants were 48 patients who produced 153 blastocysts after undergoing IVF. On the 5th day after fertilization, the researchers collected cells from each embryo **(Figure 26.21)**. After the embryos were transferred into the mothers, 37 of them resulted in healthy births. DNA samples from each baby were matched to the blastocyst cells using DNA profiling (see Chapter 12), allowing researchers to determine which embryos led to successful pregnancies and which did not. The embryonic cells were then screened using DNA microarrays (see Chapter 11) to reveal which genes were turned on and off in each embryo. Their **results** identified a large number of differences in gene expression between embryos that were destined for success and those that were not. In particular, genes for cell-to-cell communication and the ability of cells to stick together were more active in the successful embryos. Fertility researchers hope that these results will lead to tests that can identify the embryos most likely to result in pregnancy, reducing the need to implant multiple embryos and therefore reducing the likelihood of multiple pregnancy and the risks involved.

▼ Figure 26.21 A 5-day-old human embryo.



Colorized SEM 520

The Ethics of IVF

Recent research has shown that IVF babies have a slightly greater risk of birth defects than babies born from natural conception. Despite such risks and the high cost (around $10,000 for each attempt, whether it succeeds or not), IVF is now routinely performed at medical centers throughout the world and results in the birth of thousands of babies each year.

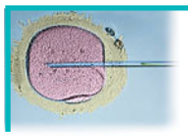
One major difference between natural and artificial fertilization is that technology offers choices that nature does not. For example, sperm can be sorted based on whether they contain an X or Y chromosome, increasing the likelihood of creating a zygote of a particular sex. Furthermore, as discussed in the Process of Science section, cells can be harmlessly removed from early embryos; they can then be tested for disease-causing (or other) genes. As analysis of the human genome progresses, the potential to screen for diseases and physical traits increases. Parents may thus have a lot of information they can use in choosing which embryos to implant.

The concept of parenthood has been greatly complicated by modern reproductive technologies. Mix-ups in fertility clinics have resulted in the implantation of embryos into the wrong women. When this happens, who has what rights? Divorcing couples have sued each other for custody of frozen embryos. An infertile couple could purchase eggs from a woman, sperm from a man, and then hire a surrogate to carry the baby. Who, then, are the baby's true parents? Each new reproductive technology raises moral and legal questions. Many of these have not yet been addressed, much less resolved, by society. All of us need to understand the science behind these complex issues so that we can make informed decisions as citizens and potential parents. ☑

☑ CHECKPOINT

Explain how up to five people can be involved in creating one baby.

Answer: A couple can hire a surrogate mother to carry an embryo created with gametes from a sperm donor and an egg donor.



High-Tech Babies EVOLUTION CONNECTION

The "Grandmother Hypothesis"

In this chapter, you have read how reproductive technologies can allow infertile couples to have babies. In recent years, technology has also made it possible for women to become pregnant after menopause, the cessation of ovulation and menstruation caused by changes in hormone levels. Menopause occurs around age 50, but in vitro fertilization has enabled some postmenopausal women to bear children up to age 70.

Given such efforts to artificially extend a woman's childbearing years, it may seem that menopause is an evolutionary disadvantage. Indeed, in most species, females retain their reproductive capacity throughout life. If evolutionary fitness is measured by the number of surviving, fertile offspring, why does menopause occur in humans? Evolutionary biologists have formed several intriguing hypotheses.

As discussed in Chapter 17, a larger brain is one of the hallmarks of human evolution. The development of a large brain requires significant time and nutrients. Humans, unlike almost every other species, continue to depend on their mothers to provide food and care for many years after weaning. Natural selection may thus have favored reproductive adaptations that promote extended maternal care. Human mothers may bear fewer children than some other animals, but each one receives a significant investment of resources and therefore has an increased chance of survival.

Some researchers speculate that menopause actually increases a woman's evolutionary fitness in the long run. Perhaps losing the ability to become pregnant allows a woman to focus her energy on caring for the children she has, rather than producing more that might not survive. Furthermore, women who can no longer bear children themselves can contribute by helping to raise their grandchildren **(Figure 26.22)**. Because a woman shares one-half of her genes with each of her children and one-quarter of her genes with each grandchild, helping to raise two grandchildren can help perpetuate as many genes to future generations as bearing one more child. Thus, even though menopause may cause a woman to have fewer children, this "grandmother hypothesis" suggests that it may actually increase the number of closely related children who will themselves reach maturity, ensuring the continuation of the postmenopausal grandmother's genes. Viewed this way, the unusual reproductive life cycle of human females is another example of biology's unifying theme of evolution.



▼ Figure 26.22 Human grandmothers often help care for young children.

Chapter Review

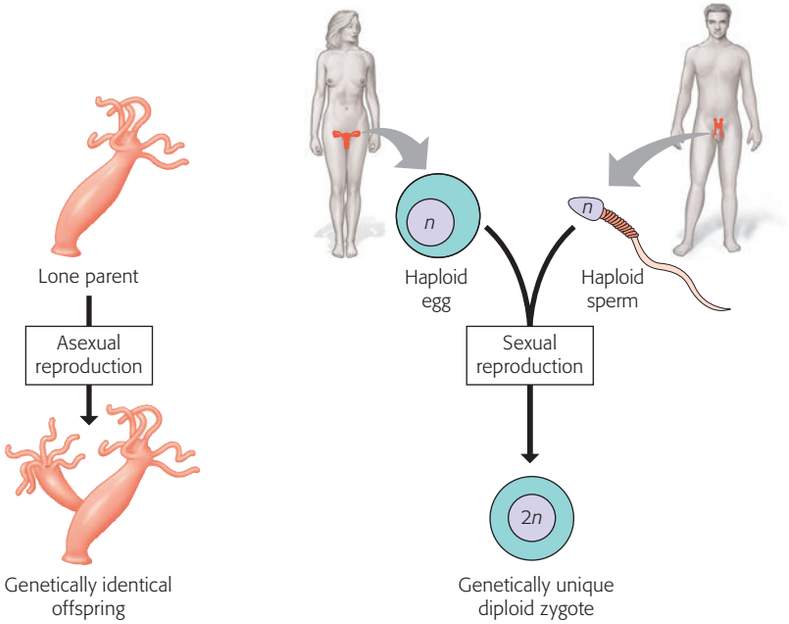
SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

Unifying Concepts of Animal Reproduction

Asexual Reproduction

In asexual reproduction, one parent produces genetically identical offspring by budding, fission, or fragmentation followed by regeneration. Asexual reproduction enables a single individual to produce many offspring rapidly, but the resulting genetically identical population may be less able to survive environmental changes.



Sexual Reproduction

Sexual reproduction increases the variation among offspring, which may enhance reproductive success in changing environments.

Human Reproduction

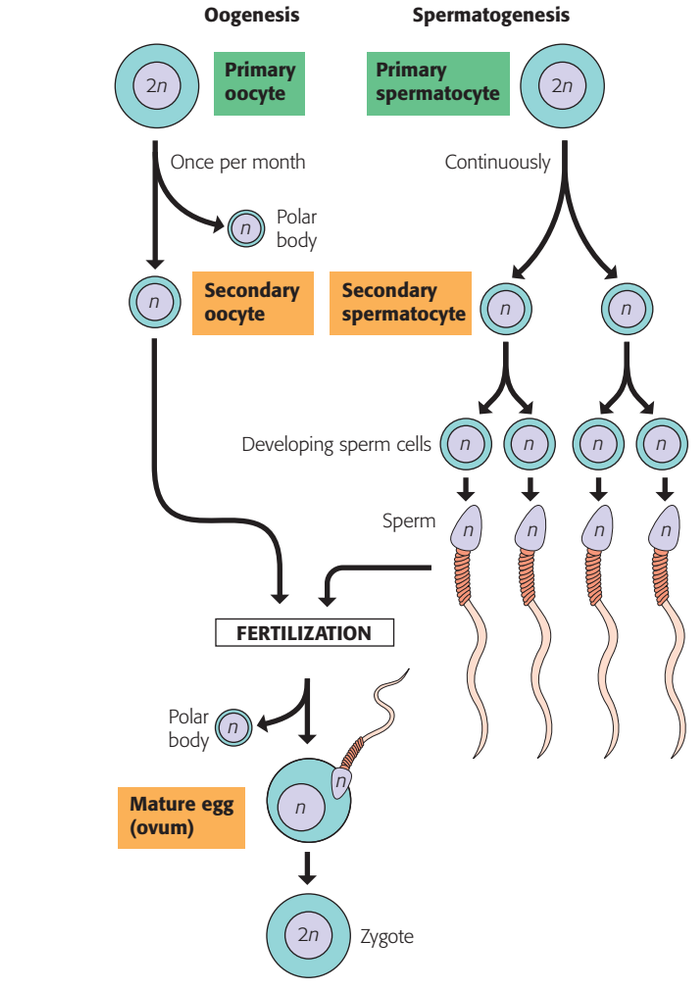
Male Reproductive Anatomy

The human reproductive system consists of a pair of gonads, ducts that carry gametes, and structures for sexual intercourse. Located in an external sac called the scrotum, a man's gonads (the testes) produce sperm, which are expelled through ducts during ejaculation. Several glands contribute to the formation of fluid that carries, nourishes, and protects sperm. This fluid and the sperm constitute semen.

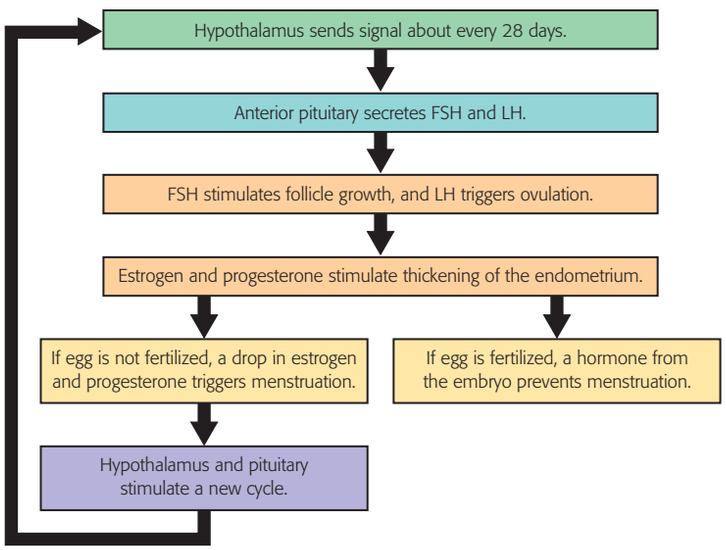
Female Reproductive Anatomy

A woman's gonads (her ovaries) contain follicles that nurture eggs and produce sex hormones. Oviducts convey eggs to the uterus, where a fertilized egg develops into a fetus. The uterus opens into the vagina, which receives the penis during intercourse and forms the birth canal.

Gametogenesis



The Female Reproductive Cycle



Reproductive Health

Contraception

Contraception is the deliberate prevention of pregnancy. Different forms of contraception block different steps in the process of becoming pregnant and have different levels of reliability. In addition to abstinence, particularly effective methods of contraception include sterilization (tubal ligation for women and vasectomy for men), barrier methods (condom or diaphragm in conjunction with a spermicide), and birth control pills.

Sexually Transmitted Diseases

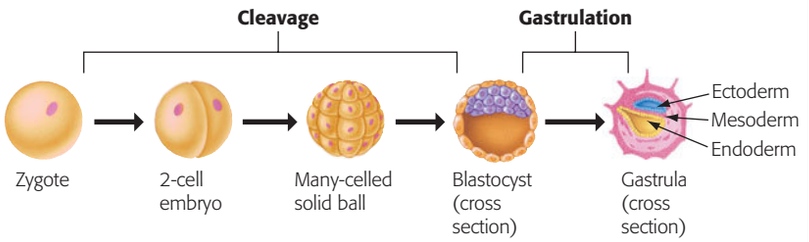
STDs are contagious diseases that can be spread by sexual contact. Viral STDs (such as AIDS, genital herpes, and genital warts) cannot be cured, whereas STDs caused by bacteria, protists, and fungi are generally curable with drugs. Abstinence or the use of latex condoms can prevent STDs.

Human Development

Fertilization

During fertilization, the union of sperm and egg to form a zygote, a sperm releases enzymes that pierce the egg's membrane; then the sperm and egg plasma membranes fuse, and the two nuclei unite. Changes in the egg membrane prevent entry of additional sperm, and the fertilized egg is stimulated to develop into an embryo.

Basic Concepts of Embryonic Development



After gastrulation, the three embryonic tissue layers give rise to specific organ systems. In a process called induction, adjacent cells and cell layers influence each other's differentiation via chemical signals. Tissues and organs take shape in a developing embryo as a result of cell shape changes, cell migration, and programmed cell death.

Pregnancy and Early Development

Pregnancy, measured as 40 weeks from the start of the last menstrual cycle, is the carrying of the developing young in the uterus. Human development begins with fertilization and cleavage in the oviduct. After about 1 week, the embryo implants itself in the uterine wall.

The Stages of Pregnancy

Human embryonic development is divided into three trimesters of about 3 months each. The most rapid changes occur during the first trimester. By 9 weeks, all organs are formed, and the embryo is called a fetus. The second and third trimesters are times of growth and preparation for birth.

Childbirth

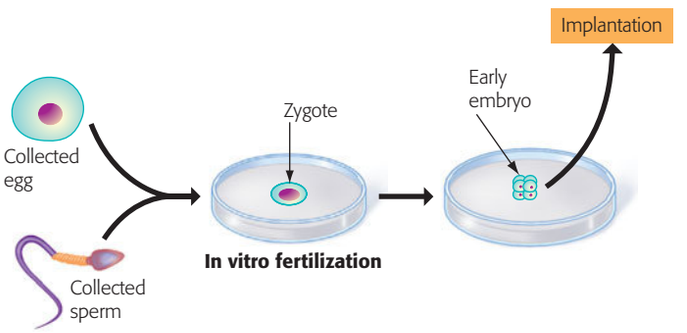
Hormonal changes induce birth. The cervix dilates, the baby is expelled by strong muscular contractions, and the placenta follows. Prolactin then stimulates milk production.

Reproductive Technologies

Infertility

Infertility, the inability to have children after one year of trying, is most often due to problems in the man, such as underproduction of sperm. Female infertility can arise from a lack of eggs or a failure to ovulate. Technologies can help treat many forms of infertility.

In Vitro Fertilization



In vitro fertilization (IVF) offers choices that the natural pathway does not, raising moral and legal issues.

SELF-QUIZ

1. Some animals, such as rotifers and aphids, are able to alternate between sexual and asexual reproduction. Under what conditions might it be advantageous to reproduce asexually? Sexually?
2. A fertility specialist determines that a patient is producing a normal amount of sperm but the semen does not contain enough of the fluids needed to nourish the sperm. Which structures are most likely responsible for this problem?
3. Match each reproductive structure with its description:

a. uterus	1. female gonad
b. vas deferens	2. site of spermatogenesis
c. oviduct	3. site of fertilization
d. ovary	4. site of gestation
e. endometrium	5. lining of uterus
f. testis	6. sperm duct

4. A woman has had several miscarriages. Her doctor suspects that a hormonal insufficiency has been causing the lining of the uterus to break down as it does during menstruation, terminating her pregnancies. Treatment with which of the following might help her remain pregnant?
   a. oxytocin
   b. HCG
   c. follicle-stimulating hormone
   d. prolactin

5. Why is it important that the hormones FSH and LH are inhibited after ovulation has occurred in the female cycle? Which female hormones inhibit FSH and LH?

6. What advantage do abstinence and condoms have over other forms of contraception?

7. How does a zygote differ from a mature egg (ovum)?
   a. A zygote has more chromosomes.
   b. A zygote is smaller.
   c. A zygote consists of more than one cell.
   d. A zygote is much larger.

8. If a baby is born missing the outer layer of skin, which of the following layers would have been the most likely site of damage in the embryo?
   a. endoderm
   b. mesoderm
   c. ectoderm
   d. stem cells

9. In an embryo, nerve cells grow out from the spinal cord and form connections with the muscles they will eventually control. What mechanism described in this chapter might explain how these cells "know" where to go and which cells to connect with?

10. A pregnant woman is two weeks past her due date, and the doctor decides to induce her labor. The natural hormone that would be needed is _____.

11. The procedure that creates a "test-tube baby" is _____. What does this term literally mean?

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

12. A typical egg cell survives about 24 hours, but some may survive up to 48 hours. A typical sperm survives 48 hours, but some may live up to 5 days. Assume that a female ovulates on day 14 of her cycle. How many days prior to ovulation and after ovulation is there a chance for pregnancy to occur? What is the total fertility window for this female?

13. A physician is trying to determine the cause of a male patient's infertility. Based on what you know about the male reproductive system, what would be the most logical things to test for?

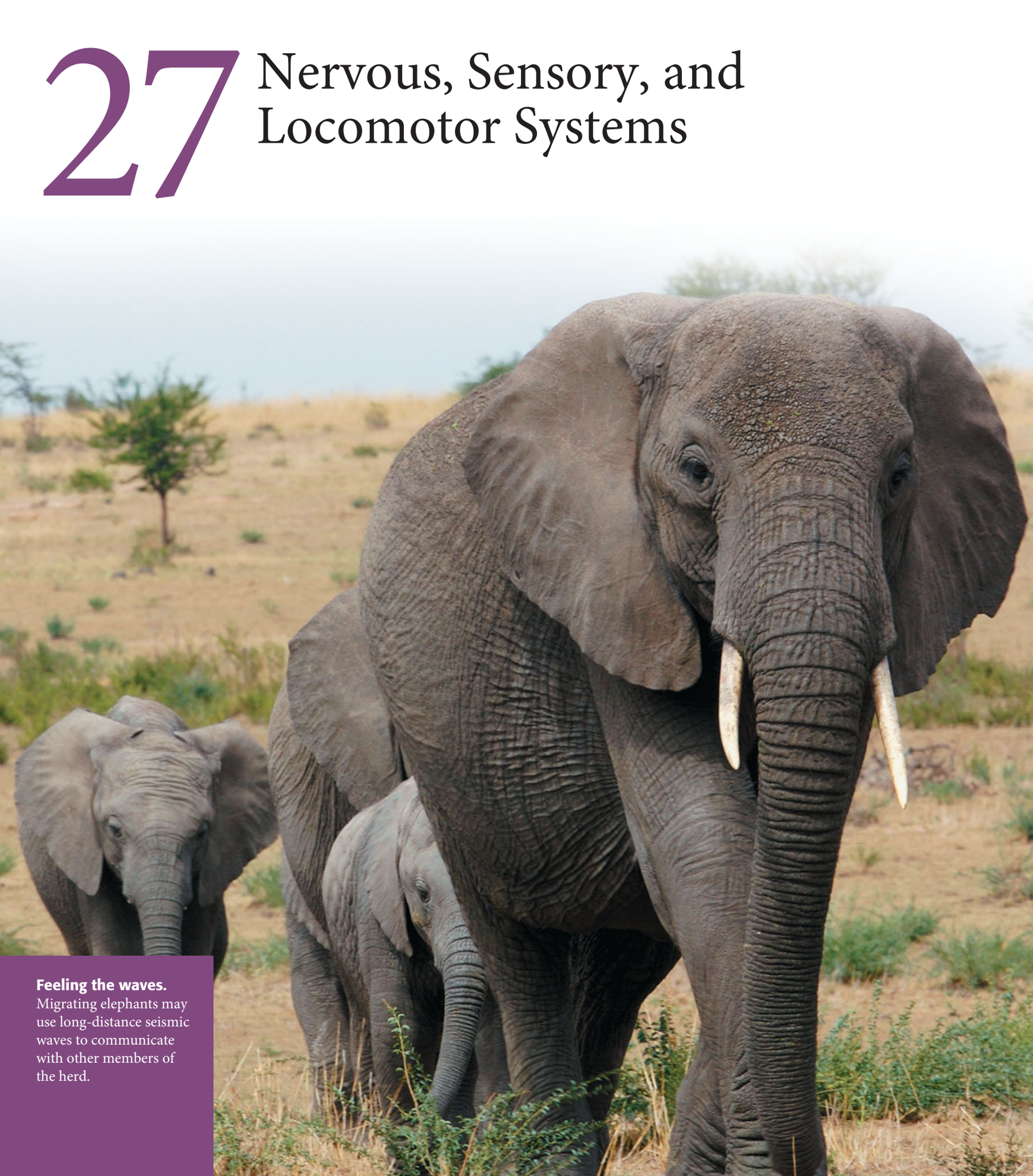
BIOLOGY AND SOCIETY

14. New technology enables doctors to save a small percentage of babies born 16 weeks prematurely. A baby born this early weighs just over 1 pound and faces months in an intensive-care nursery. The cost for care may be hundreds of thousands of dollars per infant. Some people wonder whether such a huge technological and personnel investment should be devoted to such a small number of babies. They feel that limited resources might be better directed at providing prenatal care that could prevent many premature births. What do you think? In what ways should cost influence medical decisions?

15. Some infertile couples hire a surrogate mother to have their biological child. When couples enter into an agreement with a surrogate mother, all parties sign a contract. But there have been cases where a surrogate mother signed a contract but then decided not to give up the baby to the couple who hired her. Do you think a surrogate mother should have the right to change her mind and keep the baby, even though it is not genetically hers? In some cases, the surrogate will also donate her eggs to be fertilized by the male's sperm, making the baby genetically hers. Should she have a right to change her mind after she has signed a contract and the baby is born? How should judges decide these cases? Can you suggest any laws or regulations for such situations?

16. When a couple uses in vitro fertilization to produce a baby, they are faced with some novel choices. Typically, more embryos are produced than will be used during any one procedure. Thus, a subset of prepared embryos has to be chosen for implantation. How should parents decide which embryos to use? Should they have the right to choose embryos based on the presence or absence of disease-causing genes? What about the sex of the embryo? Should parents be able to choose embryos for implantation based on any criteria? How would you distinguish acceptable criteria from unacceptable ones? Do you think such options should be legislated?

27 Nervous, Sensory, and Locomotor Systems



Feeling the waves. Migrating elephants may use long-distance seismic waves to communicate with other members of the herd.

CHAPTER CONTENTS

An Overview of Animal Nervous Systems 576
The Human Nervous System: A Closer Look 581
The Senses 587
Locomotor Systems 593

CHAPTER THREAD
Extrahuman Senses

BIOLOGY AND SOCIETY
The Seismic Sense of Elephants 575
THE PROCESS OF SCIENCE
How Do New Senses Arise? 598
EVOLUTION CONNECTION
Seeing UV 599



Extrahuman Senses BIOLOGY AND SOCIETY

The Seismic Sense of Elephants

We humans have keen senses, but many animals perceive the world in ways we cannot. For example, some bats use echolocation, emitting ultrasonic waves (high-pitched sounds above the range of human hearing) and then navigating by measuring their echoes. Many fishes detect prey by electroreception, detecting changes in the electric fields they produce using organs in their tails. Many animals—including birds, fishes, turtles, and bees—navigate using magnetoreception, the ability to detect Earth's magnetic field.

In the mid-1980s, wildlife biologists discovered that elephants, the largest land animals on Earth, can communicate using low-rumbling infrasounds, sounds too low to be heard by human ears. Under ideal conditions, such sounds can travel for 5 miles through the air, allowing elephants to communicate over long distances. While studying elephants, scientists also began to notice an unusual behavior: A group of elephants—in unison and for no apparent reason—will often freeze, lifting one foot in the air and laying their trunk along the ground. Applying sensitive listening equipment (like the instruments used to detect earthquakes), wildlife researchers discovered that the elephants are responding to a sense that humans lack: the ability to detect seismic waves, which are low-frequency vibrations in the ground.

Recent research has suggested that elephants can detect seismic waves using specialized pressure-sensing nerve endings in their feet and trunk. Such abilities may be an evolutionary adaptation that allows elephants to migrate, meet, and mate over great distances of the African savannah. Perhaps the elephants are sending specific signals to each other; after all, a typical elephant weighs 6 tons or more, so a purposeful foot stomp can produce a sizable ground wave. Or maybe the seismic activity is merely a by-product of elephant activities such as running or trumpeting. Research into the senses of these remarkable creatures remains an active and fascinating area of biology.

Although as a human you lack the animal senses described here, you are able to perceive the world and to process your perceptions. You accomplish this using your brain, which is the hub of an intricate network of structures that detect, integrate, and respond to stimuli from the environment. By examining the structure and function of the nervous, sensory, and motor systems, we will explore how stimuli are translated into responses within the body. Let's begin by focusing on the processing center, the nervous system.

An Overview of Animal Nervous Systems

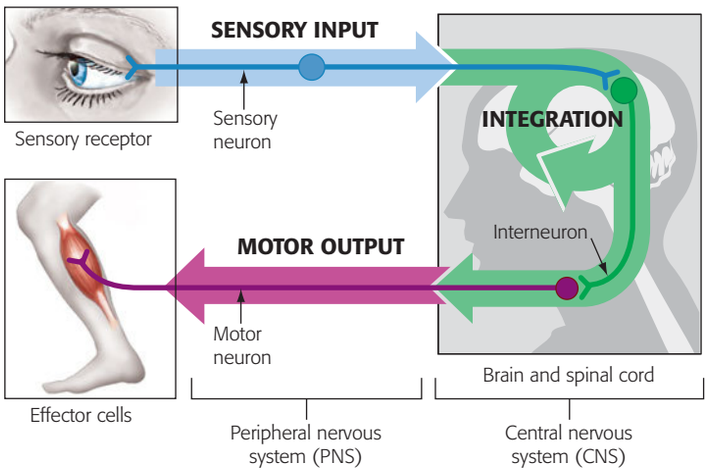
The **nervous system** forms a communication and coordination network throughout an animal's body. Nervous systems are the most intricately organized data processing systems on Earth. Your brain, for instance, contains an estimated 100 billion **neurons**, nerve cells that carry electrical signals from one part of the body to another. Each neuron may communicate with thousands of others, forming networks that enable us to move, perceive our surroundings, learn, and remember. In this section, we'll focus on features that are common to the nervous systems of all animals.

Organization of Nervous Systems

The nervous systems of most animals have two main anatomical divisions. The **central nervous system (CNS)** consists of the brain and, in vertebrates, the spinal cord. The **peripheral nervous system (PNS)** is made up mostly of nerves that carry signals into and out of the CNS. A **nerve** is a communication line made from cable-like bundles of neuron fibers tightly wrapped in connective tissue.

Figure 27.1 highlights the three interconnected functions of the nervous system and the three types of neurons that carry out these functions. **Sensory input** is the process of sending signals from sensory receptors, such as light-detecting cells of the eyes, to the CNS. **Sensory neurons** in the PNS (shown in blue) convey this information. **Integration** is the analysis and interpretation of sensory signals and the formulation of appropriate responses. **Interneurons** (green), located entirely within the CNS, perform integration. **Motor output** is the process of sending signals from the integration centers to **effector cells**, such as muscle cells, that perform the body's responses (moving a leg in this example). Motor output is performed by **motor neurons** in the PNS (purple). ☑

▼ **Figure 27.1 Organization of a nervous system.** This figure shows only one neuron of each functional type, but body activity actually involves many. A simplified version of this figure will keep you oriented throughout the chapter.



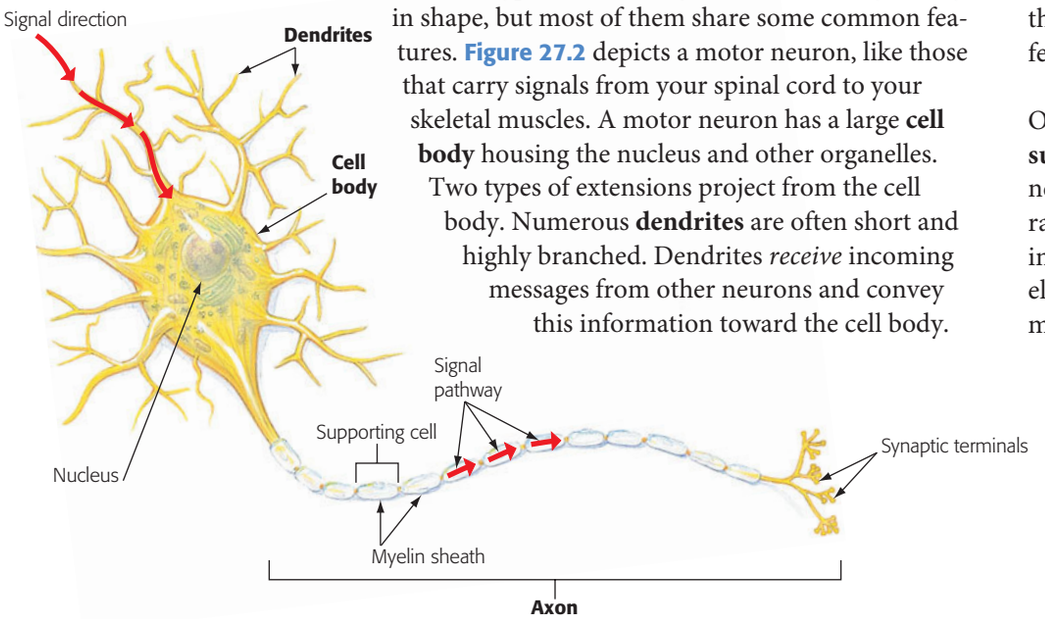
☑ CHECKPOINT

Arrange the following neurons into the correct sequence for information flow from stimulus to response: interneuron, sensory neuron, motor neuron.

Answer: sensory neuron, interneuron, motor neuron

Neurons

The three types of neurons just described vary widely in shape, but most of them share some common features. Figure 27.2 depicts a motor neuron, like those that carry signals from your spinal cord to your skeletal muscles. A motor neuron has a large **cell body** housing the nucleus and other organelles. Two types of extensions project from the cell body. Numerous **dendrites** are often short and highly branched. Dendrites *receive* incoming messages from other neurons and convey this information toward the cell body.



The other type of extension, a single long fiber called an **axon**, *transmits* signals toward another neuron or toward an effector cell. Some axons, such as the ones that reach from your spinal cord to muscle cells in your feet, can be over a meter long.

Neurons make up only part of a nervous system. Outnumbering neurons by as many as 50 to 1 are **supporting cells** that protect, insulate, and reinforce the neurons. In many vertebrates, axons that convey signals rapidly are enclosed along most of their length by an insulating material called the **myelin sheath**. The myelin sheath is a chain of bead-like supporting cells. The myelin sheath helps speed electrical transmission

◄ **Figure 27.2 Structure of a motor neuron.** This diagram shows a motor neuron. The flow of the electrical signal through a neuron follows this path: dendrite → cell body → axon.

along an axon. In the human nervous system, signals can travel along a myelinated axon about 150 m/sec (over 330 mph!), which means that a command from your brain can make your fingers move in just a few milliseconds.

The debilitating autoimmune disease multiple sclerosis (MS) leads to a gradual destruction of the myelin sheath by the individual's own immune system. This causes a progressive loss of the ability to send signals and control muscles. MS has no cure, but drugs that suppress the immune system can relieve symptoms and slow its progress.

What causes multiple sclerosis?

Returning to Figure 27.2, notice that the axon ends in a cluster of branches. A typical axon has hundreds or thousands of these branches, each with a synaptic terminal at the very end. As we will see later, each **synaptic terminal** relays signals to another neuron or to an effector cell such as a muscle cell. With the basic structure of a neuron in mind, let's take a closer look at how neurons convey signals. ☑

Sending a Signal through a Neuron

To understand nerve signals, we must first study a resting neuron, one that is not transmitting a signal. A resting neuron has potential energy that can be put to work to send nerve signals from one part of the body to another. This potential energy exists in the form of an electrical charge difference across the neuron's plasma membrane. The inside of the cell is negatively charged relative to the outside. Because opposite charges tend to move toward each other, the membrane stores energy by holding opposite charges apart, much like a battery. This difference in charge (voltage) that exists across the plasma membrane of a resting neuron is called the **resting potential**.

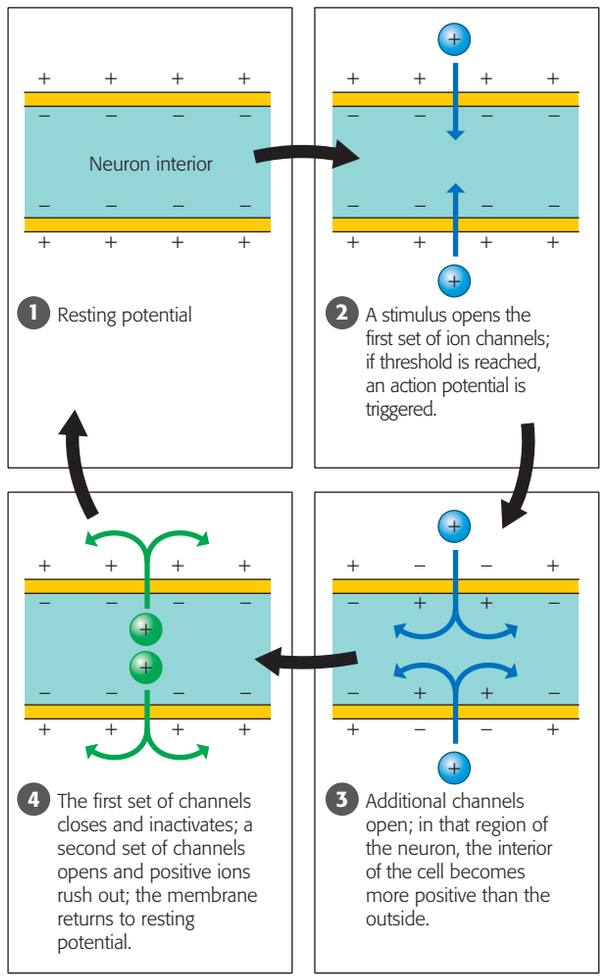
The resting potential is caused by the presence of differently charged ions (primarily Na^+ and K^+) on either side of the membrane. What keeps the ions apart? As mentioned in Chapter 5, the hydrophobic interior of the membrane's phospholipid bilayer doesn't let ions pass through. However, the membrane has protein channels and pumps that can allow positive ions across. By carefully controlling the passage of these ions, a neuron can tap into the energy stored in the resting potential.

The Action Potential

Turning on a flashlight uses the potential energy stored in a battery to create light. In a similar way, stimulating a neuron's plasma membrane can trigger the use of the membrane's potential energy to generate an electrical nerve signal. A **stimulus** is any factor that causes a nerve signal to be generated. Examples of stimuli include light, sound, touching a hot surface, or a chemical signal from another neuron. A stimulus of sufficient strength can trigger an **action potential**, a nerve signal that carries information along a neuron. The signal is actually a self-propagating change in the voltage across the plasma membrane.

Figure 27.3 shows the series of events involved in generating an action potential. As you'll see, two different sets of ion channels are involved in this process. ❶ At first, the membrane is at its resting potential, positively charged outside and negatively charged inside. ❷ A stimulus triggers the opening of a few of the first set of ion channels in the membrane (represented by the blue arrows), allowing a few positive ions to enter the neuron. This tiny change makes the inside surface of the membrane slightly less negative than before. If the stimulus is strong enough, a sufficient number of channels open to reach the **threshold**, the minimum change in a membrane's voltage that must occur to trigger the action potential. ❸ Once threshold is reached, more of these channels open and more positive ions rapidly rush in. As a result, the interior of this region of the cell becomes positively charged with respect to the outside. ❹ This electrical change triggers the closing of the first set of channels. Meanwhile, a second set of channels opens (green arrows), allowing other positive ions to diffuse rapidly out and returning the membrane to its resting potential. Within a living neuron, this whole process takes just a few milliseconds, meaning a neuron can produce hundreds of nerve signals in a second.

▼ Figure 27.3 Generation of an action potential.



☑ CHECKPOINT

Arrange the following parts of a neuron in the sequence that a signal would pass through them: axon, cell body, dendrite, synaptic terminal. For each part, indicate whether one or many are found in a typical neuron.

Answer: *many dendrites → one cell body → one axon → many synaptic terminals*

Propagation of the Signal

An action potential is a localized electrical event—a rapid change from the resting potential at a specific place along the neuron. A nerve signal starts out as an action potential generated near the cell body of the neuron. To function as a long-distance signal, this local event must be passed along the neuron. This process is like tipping the first of a row of standing dominoes: The first domino does not travel along the row, but its fall is relayed to the end of the row, one domino at a time.

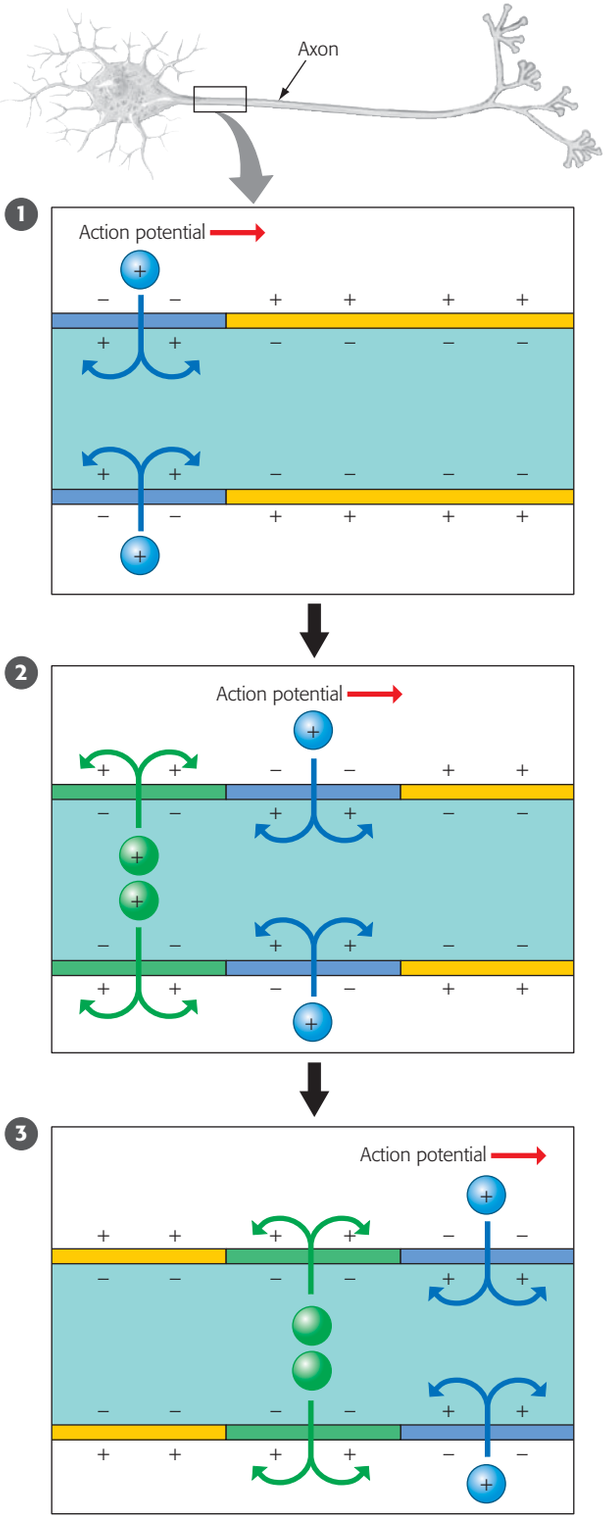
Figure 27.4 shows the changes that occur in part of an axon as a nerve signal passes from left to right. Let's start by focusing only on the axon region at the far left in each panel. ❶ When this region of the axon (blue) has its first set of channels open, positive ions diffuse inward (blue arrows), and an action potential is generated. ❷ That same region then opens the second set of channels, allowing other positive ions to diffuse out of the axon (green arrows) while closing the first set of channels that allow ions in. ❸ A short time later, we would see no action potential at this (far left) spot because the membrane here has restored itself and returned to its resting potential.

Now let's see how these events lead to the "domino effect" of a nerve signal. In step 1 of the figure, the blue arrows pointing sideways within the axon indicate local spreading of the electrical changes caused by the positive ions entering the neuron. These changes trigger the opening of the first set of channels in the membrane just to the right of the action potential. As a result, a second action potential is generated, as indicated by the blue region in step 2. In the same way, a third action potential is generated in step 3. At each point along the neuron, the action potential triggers changes in the adjacent region that result in propagation of the action potential along the neuron.

So why are action potentials propagated in only one direction along the axon (left to right in the figure)? As the blue arrows indicate, local electrical changes do spread in both directions in the axon. However, these changes cannot open the first set of channels and generate an action potential when these channels are inactivated (step 4 in Figure 27.3). Thus, an action potential cannot be generated in the regions where the second set of channels is open and positive charge is leaving the axon (green in Figure 27.4).

Action potentials are all-or-none events; that is, they are the same no matter how strong or weak the stimulus that triggers them (as long as threshold is reached). This is like pulling a trigger: It doesn't matter how gently or roughly you pull the trigger, once it reaches a certain point, the gun is fired just the same. How, then, do action potentials relay different intensities of information? Such information can be achieved by sending more action potentials in a given amount of time. For example, in the neurons connecting your ears to your brain, loud sounds generate more action potentials per second than quiet sounds. Once your CNS receives information in the form of action potentials, it can process the information and formulate a response to it. ☑

▼ Figure 27.4 Propagation of an action potential along an axon.



☑ CHECKPOINT

In what way is an action potential an example of positive feedback?

Answer: Positive feedback occurs when the result of a process further stimulates that process. The opening of channels caused by stimulation of the neuron changes the membrane potential, and this change causes more channels to open.

Passing a Signal from a Neuron to a Receiving Cell

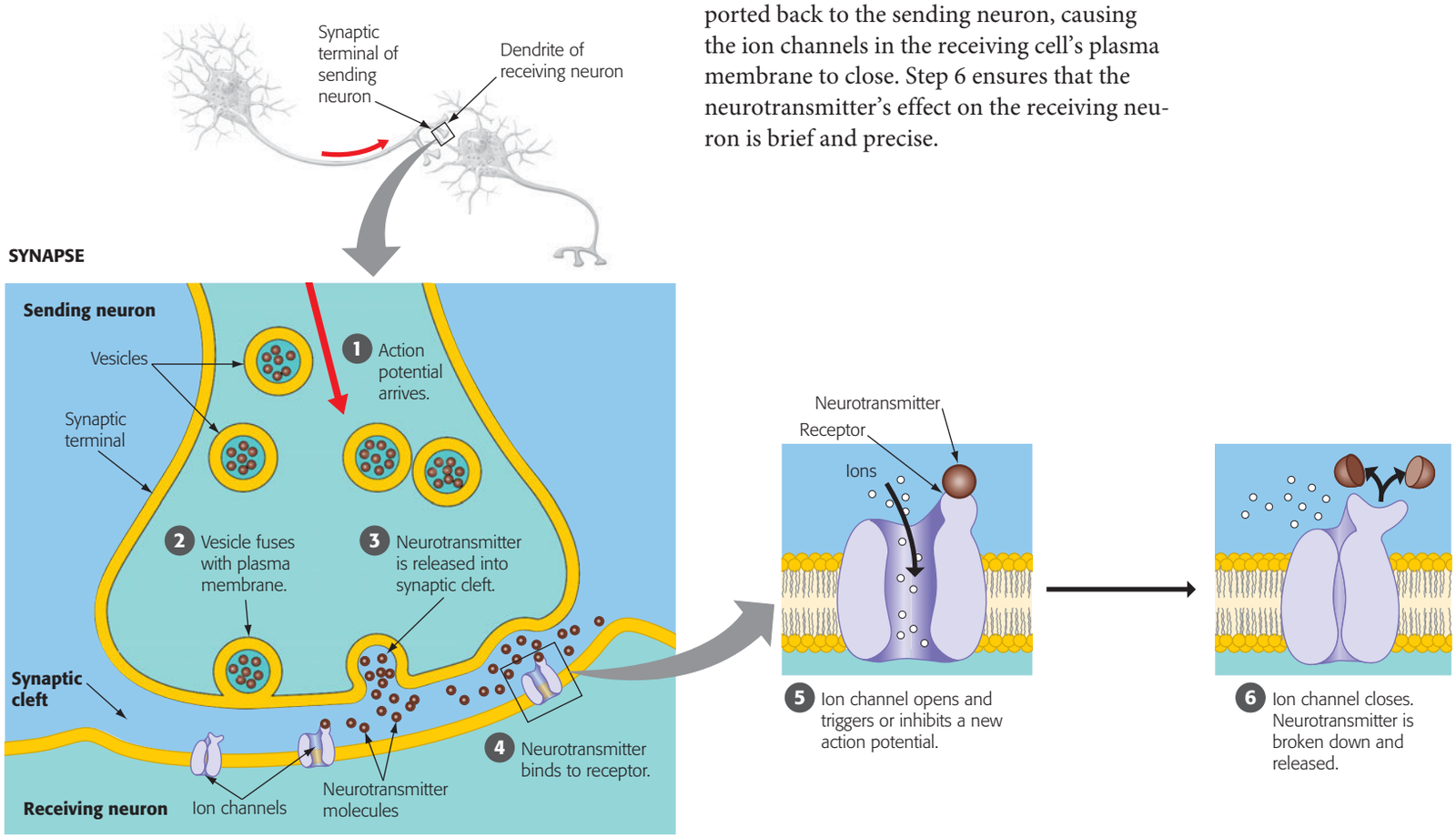
If an action potential travels in one direction along a neuron, what happens when the signal arrives at the end of the neuron? To continue conveying information, the signal must be passed to another cell. This occurs at a **synapse**, or relay point, between a neuron and a receiving cell. The receiving cell can be another neuron or an effector cell such as a muscle cell or endocrine cell.

Synapses come in two varieties: electrical and chemical. In an electrical synapse, electric current passes directly from one neuron to the next. In the human body, electrical synapses are found in the heart and digestive tract, where they help maintain steady, rhythmic muscle contractions. Chemical synapses are prevalent in most other organs, including skeletal muscles, and in the central nervous system.

Chemical synapses have a narrow gap, called the **synaptic cleft**, separating the synaptic terminal of the sending neuron from the receiving cell **(Figure 27.5)**. When the action potential (an electrical signal) reaches the end of the sending neuron, it is converted to a chemical signal consisting of molecules of neurotransmitter. A **neurotransmitter** is a chemical that carries information from a nerve cell to another cell that will react, such as another nerve cell or an effector cell. Once a neurotransmitter conveys a chemical signal from the sending neuron, an action potential may then be generated in the receiving cell.

Let's follow the events that occur at a synapse between two neurons in Figure 27.5. 1 An action potential (red arrow) arrives at the synaptic terminal. 2 The action potential causes vesicles filled with neurotransmitter ( ) to fuse with the plasma membrane of the sending neuron. 3 The fused vesicles release their neurotransmitter molecules into the synaptic cleft. 4 The released neurotransmitter molecules diffuse across the cleft and bind to complementary receptors on ion channel proteins in the receiving neuron's plasma membrane. 5 The binding of neurotransmitter to receptors opens the ion channels. With the channels open, ions can diffuse into or out of the receiving neuron. In many cases, this triggers a new action potential; in other cases, a neurotransmitter inhibits the generation of an action potential. 6 The neurotransmitter is broken down or transported back to the sending neuron, causing the ion channels in the receiving cell's plasma membrane to close. Step 6 ensures that the neurotransmitter's effect on the receiving neuron is brief and precise.

Figure 27.5 Neuron communication at a synaptic cleft.



Chemical synapses can process extremely complex information. A neuron may receive input from hundreds of other neurons via thousands of synaptic terminals (Figure 27.6). The inputs can be highly varied because each sending neuron may secrete a different quantity or kind of neurotransmitter. These factors account for the nervous system's ability to process huge amounts of complex stimuli and formulate appropriate responses. ☑

☑ CHECKPOINT

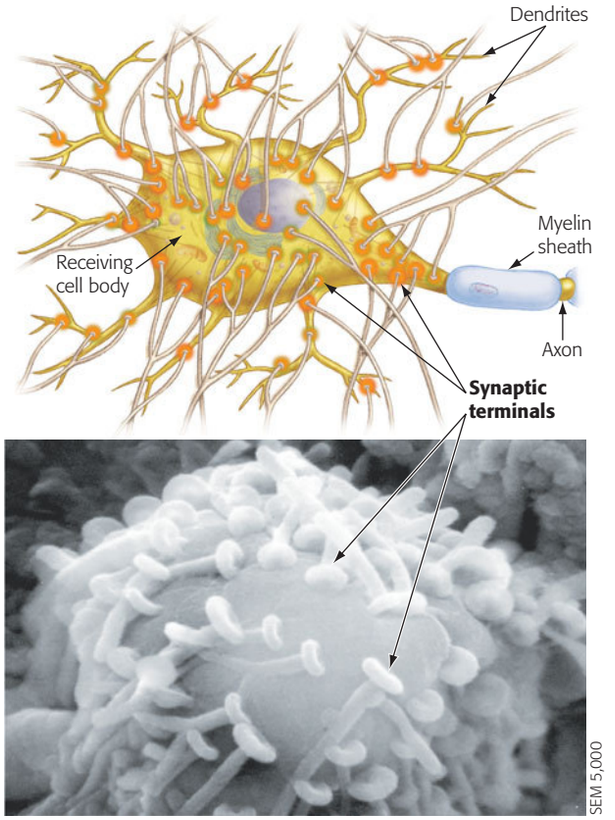
How does the structure of a synapse ensure that signals pass only in one direction, from a sending neuron to a receiving cell?

Answer: At the synapse, only the sending neuron releases a neurotransmitter, and only the receiving cell has receptors to receive the neurotransmitter.

Neurotransmitters

A variety of small molecules can act as neurotransmitters, including amines and peptides. The amines are neurotransmitters derived from amino acids. Examples include serotonin, dopamine, epinephrine, and norepinephrine. Serotonin and dopamine affect sleep, mood, attention, and learning. Imbalances of amines are associated with various disorders. For example, reduced levels of norepinephrine and serotonin have been linked to some types of depression. The degenerative illness Parkinson's disease is associated with a lack of dopamine in the brain, and an excess of dopamine is linked to schizophrenia.

Many peptides (short chains of amino acids) also serve as neurotransmitters. One class of such peptides is the endorphins, which also act as hormones. Endorphins decrease our perception of pain during times of physical or emotional stress. Endorphins may be released in response to a wide variety of stimuli, including traumatic injury, muscle fatigue, and even eating certain foods like chocolate.



▲ **Figure 27.6 A neuron's multiple synaptic inputs.** As shown in this drawing and micrograph, a single neuron may receive signals from hundreds of other neurons via thousands of synaptic terminals (shown in orange).

☑ CHECKPOINT

What determines whether a neuron is affected by a specific neurotransmitter?

Answer: To be affected by a particular neurotransmitter, a neuron must have specific receptors for that neurotransmitter in its membrane.

Drugs and the Brain

Many drugs, including common ones such as caffeine, nicotine, and alcohol, affect the actions of neurotransmitters at the brain's trillions of synapses. Caffeine, found in coffee, tea, chocolate, and many soft drinks and energy drinks, counters the effects of inhibitory neurotransmitters, ones that normally suppress nerve signals. This is why caffeine tends to stimulate you and keep you awake. Nicotine acts as a stimulant by binding to and activating receptors for a neurotransmitter called acetylcholine. Alcohol is a strong depressant; its precise effect on the nervous system is not yet known, but it seems to increase the effects of another inhibitory neurotransmitter.

Many prescription drugs used to treat psychological disorders alter the effects of neurotransmitters. Tranquilizers such as diazepam (Valium) and alprazolam (Xanax) activate the receptors for an inhibitory neurotransmitter. In other cases, a drug may physically block a receptor, preventing a neurotransmitter from binding, thereby reducing its effect. For instance, some drugs used to treat schizophrenia block dopamine receptors. Some drugs used to treat attention deficit hyperactivity disorder (ADHD), such as methylphenidate (Ritalin), are chemically similar to the neurotransmitters dopamine and norepinephrine. Scientists think that ADHD medications block the reuptake of these neurotransmitters, but do not yet understand their precise actions in the brain.

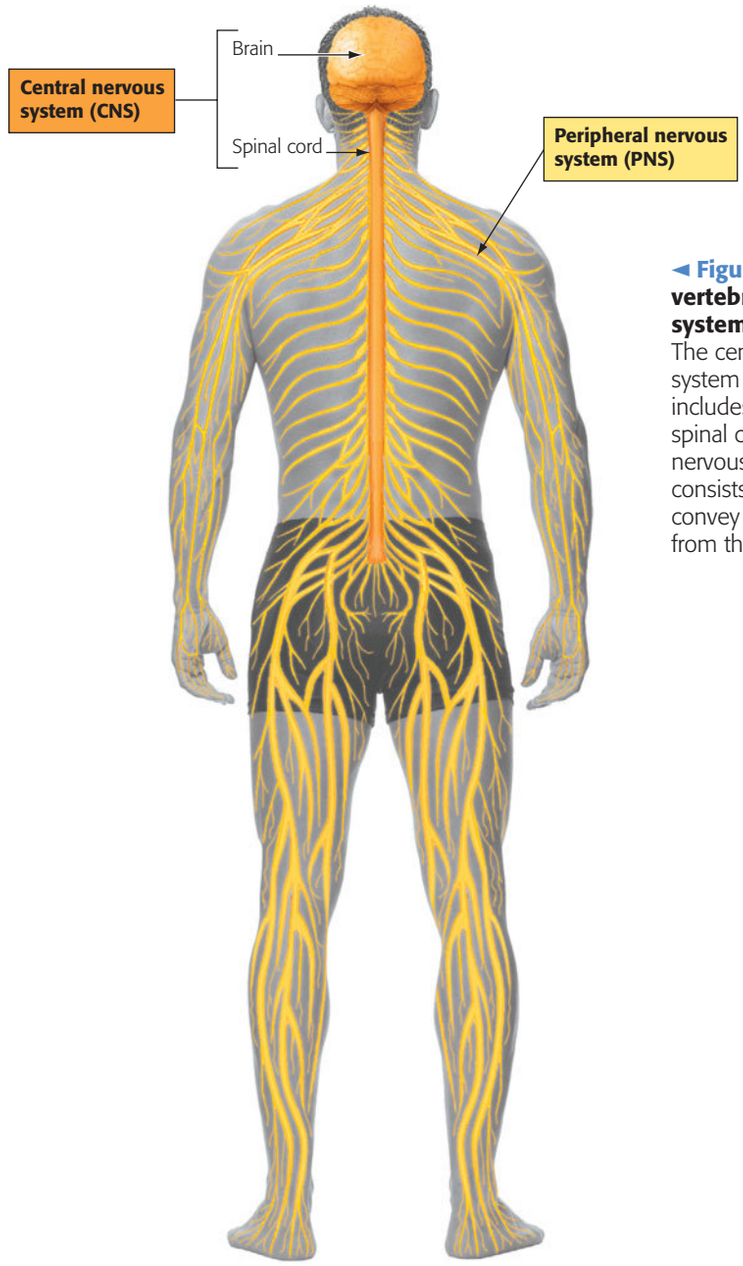
What about illegal drugs? Stimulants such as amphetamines and cocaine increase the release and availability of norepinephrine and dopamine at synapses. Abuse of these drugs can therefore produce symptoms resembling schizophrenia. LSD and mescaline may produce their hallucinatory effects by activating serotonin and dopamine receptors. The active ingredient in marijuana binds to brain receptors normally used by other neurotransmitters that seem to play a role in pain, depression, appetite, memory, and fertility. Opiates—morphine, codeine, and heroin—bind to endorphin receptors, reducing pain and producing euphoria. Opiates are thus usually prescribed to relieve pain.

While the drugs mentioned here have the ability to increase alertness and a sense of well-being or to reduce physical and emotional pain, they also have the potential to disrupt the brain's finely tuned neural pathways, altering the chemical balances that are the product of millions of years of evolution. ☑

The Human Nervous System: A Closer Look

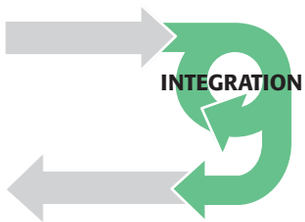
To this point, we have concentrated on cellular mechanisms that are fundamental to nearly all animal nervous systems. Although there is remarkable uniformity throughout the animal kingdom in the way nerve cells function, there is great variety in how nervous systems as a whole are organized. For the rest of this chapter, we'll focus on vertebrates, with particular emphasis on human systems.

Vertebrate nervous systems are diverse in both structure and level of sophistication—the brains of dolphins and humans are much more complex than the brains of frogs and fishes, for instance. However, some features are common to the nervous systems of all vertebrates. All have a nervous system that is concentrated at the head end, and all have a central nervous system (CNS) distinct from a peripheral nervous system (PNS) **(Figure 27.7)**.



◄ Figure 27.7 A vertebrate nervous system (back view). The central nervous system (CNS) of humans includes the brain and the spinal cord. The peripheral nervous system (PNS) consists of nerves that convey information to and from the CNS.

The Central Nervous System



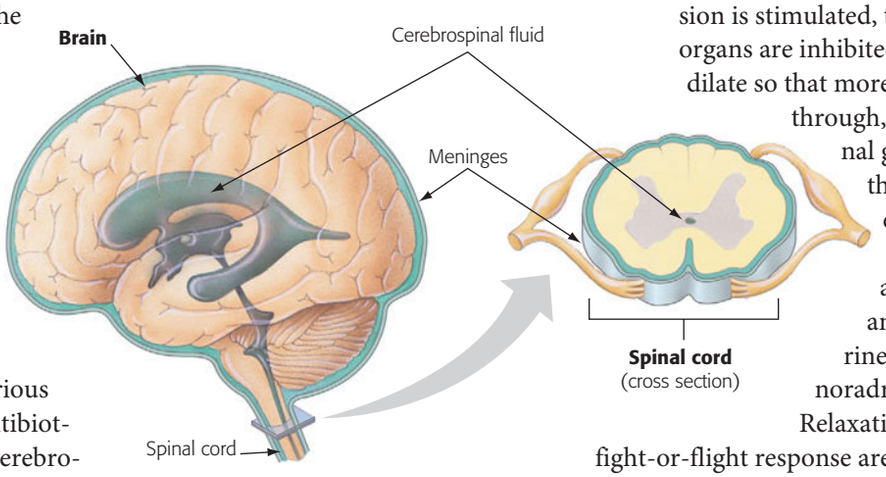
The vertebrate central nervous system integrates information coming from the senses and transmits signals that produce responses. In all vertebrates, the brain and spinal cord make up the CNS. The **spinal cord**, a jellylike bundle of nerve fibers, lies inside the spine. The spinal cord acts as the central communication conduit between the brain and the rest of the body. Millions of nerve fibers within the cord carry motor information from the brain to the muscles, while other fibers convey sensory information (such as touch, pain, and body position) from the body to the brain. The spinal cord acts like a telephone cable jam-packed with wires, each of which carries messages between the central hub and relay centers for outlying areas. In humans, the spinal cord is well protected by the bony spinal column. However, a traumatic blow to the spinal column can crush the delicate nerve bundles and prevent signals from passing. The result may be a debilitating injury. Such trauma along the back can cause paraplegia—paralysis of the lower half of the body. Trauma higher up on the spinal column can cause quadriplegia—paralysis from the neck down. Such injuries may be permanent because the nerves of the spinal cord, unlike many other body tissues, cannot be repaired.

Why can't paralysis be cured?

The master control center of the nervous system, the **brain**, includes homeostatic centers that keep the body functioning smoothly, sensory centers that integrate data from the sense organs, and (in humans, at least) centers of emotions and intellect. The brain also sends out motor commands to muscles.

Both the brain and spinal cord contain spaces filled with a liquid called **cerebrospinal fluid** that cushions the CNS and helps supply it with nutrients, hormones, and white blood cells (Figure 27.8). Also protecting the brain and spinal cord are layers of connective tissue called **meninges**. If the cerebrospinal fluid becomes infected by bacteria or viruses, the meninges may become inflamed, a condition called meningitis. Viral meningitis is generally not harmful, while bacterial meningitis can be serious if not treated with antibiotics. Infection of the cerebrospinal fluid can be detected by a spinal tap, a procedure that involves inserting a narrow needle through the spinal column to collect a sample of cerebrospinal fluid. ☑

▼ **Figure 27.8 Fluid-filled spaces of the vertebrate CNS.** Spaces in the brain and spinal cord are filled with cerebrospinal fluid, which helps to cushion and supply nutrients to the CNS.



☑ CHECKPOINT

Name the two structures that make up the vertebrate central nervous system.

Answer: the brain and spinal cord

The Peripheral Nervous System

The vertebrate peripheral nervous system (PNS) is divided into two functional components: the voluntary nervous system and the autonomic nervous system (Figure 27.9). As part of the voluntary nervous system, neurons of the **motor system** carry signals to skeletal muscles, mainly in response to external stimuli. When you walk, for instance, these neurons carry commands that make your legs move. The control of skeletal muscles is usually voluntary, as when you walk, but can also be involuntary, as in the knee-jerk reflex.

The **autonomic nervous system** regulates the internal environment by controlling smooth and cardiac muscles and the organs and glands of the digestive, cardiovascular, excretory, and endocrine systems. This control is generally involuntary. The autonomic nervous system contains two sets of neurons with opposing effects on most body organs. One set, called the **parasympathetic division**, primes the body for activities that gain and conserve energy for the body ("rest and digest"). These effects include stimulating the digestive organs, decreasing the heart rate, and narrowing the bronchi, which correlates with a decreased breathing rate. The other set of neurons in the autonomic nervous system, the **sympathetic division**, tends to have the opposite effect, preparing the body for intense, energy-consuming activities, such as fighting, fleeing, or competing in a strenuous game ("fight or flight"). When this division is stimulated, the digestive organs are inhibited, the bronchi dilate so that more air can pass through, and the adrenal glands secrete the hormones epinephrine (also called adrenaline) and norepinephrine (also called noradrenaline). Relaxation and the fight-or-flight response are opposite extremes. Your body usually operates somewhere in between, with most of your organs receiving both sympathetic and parasympathetic signals. The opposing signals adjust an organ's activity to a suitable level.

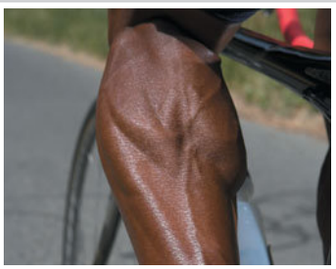
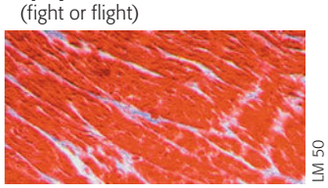
As carriers of command signals, the motor neurons of the parasympathetic and sympathetic systems constitute lower levels of the nervous system's hierarchy. In the next section, we'll take a closer look at the highest level of the hierarchy, the brain. ☑

☑ CHECKPOINT

How would a drug that inhibits the parasympathetic nervous system affect your pulse?

Answer: Your pulse rate would increase.

▼ **Figure 27.9 Functional divisions of the vertebrate PNS.**

PERIPHERAL NERVOUS SYSTEM	
Voluntary nervous system	**Autonomic nervous system** (involuntary)
	• **Parasympathetic division** (rest and digest) • **Sympathetic division** (fight or flight) 
Voluntary leg muscles	Involuntary heart muscle

The Human Brain

Composed of up to 100 billion intricately organized neurons, with a much larger number of supporting cells, the human brain is more powerful than the most sophisticated computer. The brain is divided structurally into three regions: the hindbrain, the midbrain, and the forebrain **(Figure 27.10** and **Table 27.1)**.

Two sections of the hindbrain (blue in Figure 27.10), the **medulla oblongata** and the pons, and the midbrain (purple) make up a functional unit called the **brainstem**. All of the sensory and motor neurons carrying information to and from other brain regions pass through the brainstem. The brainstem serves as a sensory filter, selecting which information to pass on. It also regulates sleep and arousal and helps coordinate body movements, such as walking. Table 27.1 lists some of the other functions of the medulla oblongata, pons, and midbrain.

Also part of the hindbrain, the **cerebellum** (light blue in the figure) is a planning center for body movements. The cerebellum receives sensory information about the position of limbs and the length of muscles, as well as information from the auditory and visual systems. It also receives input from the motor pathways, telling it which motor actions are being carried out. The cerebellum uses this information to provide coordination of movement and balance. When you step off a curb, for instance, your cerebellum evaluates your body position and relays a plan for your next movements.

The most sophisticated integrating centers are found in the forebrain (orange and yellow in Figure 27.10); they are the thalamus, the hypothalamus, and the cerebrum. The thalamus contains most of the cell bodies of neurons that relay information to the cerebral cortex, the most extensive portion of the cerebrum. The thalamus first sorts data into categories (all the touch signals from a hand, for instance). It also suppresses some signals and enhances others. The thalamus then sends the sorted information on to the appropriate brain centers for further interpretation and integration.

In Chapter 25, we saw that the hypothalamus controls the pituitary gland and the secretion of many hormones (see Figures 25.5 and 25.6). The **hypothalamus** also regulates body temperature, blood pressure, hunger, thirst, the sex drive, and the fight-or-flight response, and it helps us experience emotions, such as rage and pleasure. A "pleasure center" in the hypothalamus could also be called an addiction center, for it is strongly affected by certain addictive drugs, such as amphetamines and cocaine. Another part of the hypothalamus functions as an internal timekeeper, our biological clock. Receiving visual input from the eyes, the clock maintains our daily biological rhythms, such as cycles of sleepiness and hunger. ☑

☑ CHECKPOINT

Which brain structure—the cerebellum or the cerebrum—contains sophisticated thinking centers?

Answer: *the cerebrum*

▼ Figure 27.10 The main parts of the human brain.

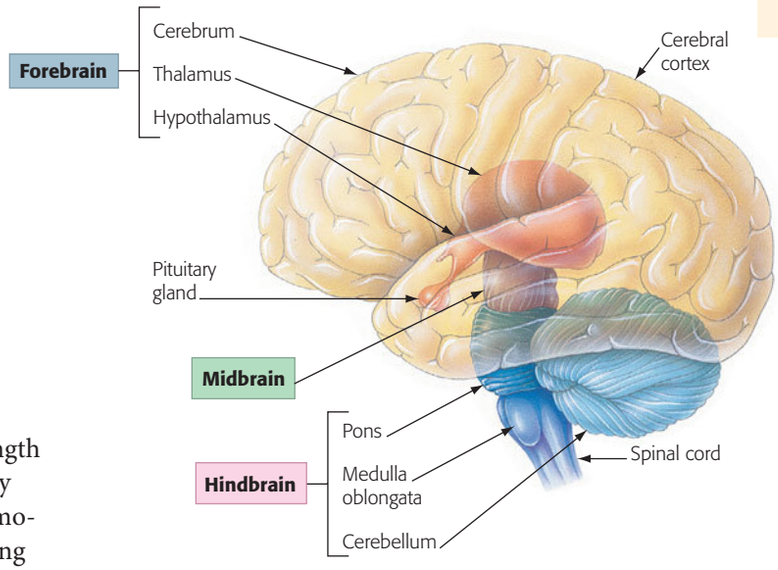


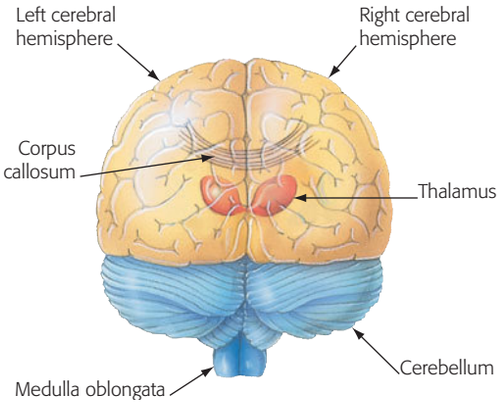
Table 27.1 Structure and Function of the Human Brain

Brain Structure	Major Functions
Brainstem	Conducts data to and from other brain centers; helps maintain homeostasis; coordinates body movement
Medulla oblongata	Controls breathing, circulation, swallowing, digestion
Pons	Controls breathing
Midbrain	Receives and integrates auditory data; coordinates visual reflexes; sends sensory data to higher brain centers
Cerebellum	Coordinates body movement; learns and remembers motor responses
Thalamus	Serves as input center for sensory data going to the cerebrum and as output center for motor responses leaving the cerebrum; sorts data
Hypothalamus	Serves as homeostatic control center; controls pituitary gland; acts as biological clock
Cerebrum	Performs sophisticated integration; involved in memory, learning, speech, emotions; formulates complex behavioral responses

The Cerebral Cortex

The **cerebrum**, the largest and most complex part of our brain, consists of right and left cerebral hemispheres (Figure 27.11). A thick band of nerve fibers called the **corpus callosum** connects the cerebral hemispheres, enabling them to process information together.

The **cerebral cortex** is a highly folded layer of tissue that forms the surface of the cerebrum (see Figure 27.10). Although less than 5 mm (0.2 inch) thick (thinner than a pencil), the human cerebral cortex accounts for over 80% of the total brain mass. It contains some 10 billion neurons and hundreds of billions of synapses. Its intricate neural circuitry helps produce our most distinctive human traits: reasoning and mathematical abilities, language skills, imagination, artistic talent, and personality traits. Assembling information it receives from our eyes, ears, nose, taste buds, and touch sensors, the cortex creates our sensory perceptions—what we are actually aware of when we see, hear, smell, taste, or touch. The cerebral cortex also regulates our voluntary movements.



▲ **Figure 27.11 A rear view of the brain.** The large cerebrum (yellow) consists of left and right cerebral hemispheres connected by a thick band of nerves called the corpus callosum.

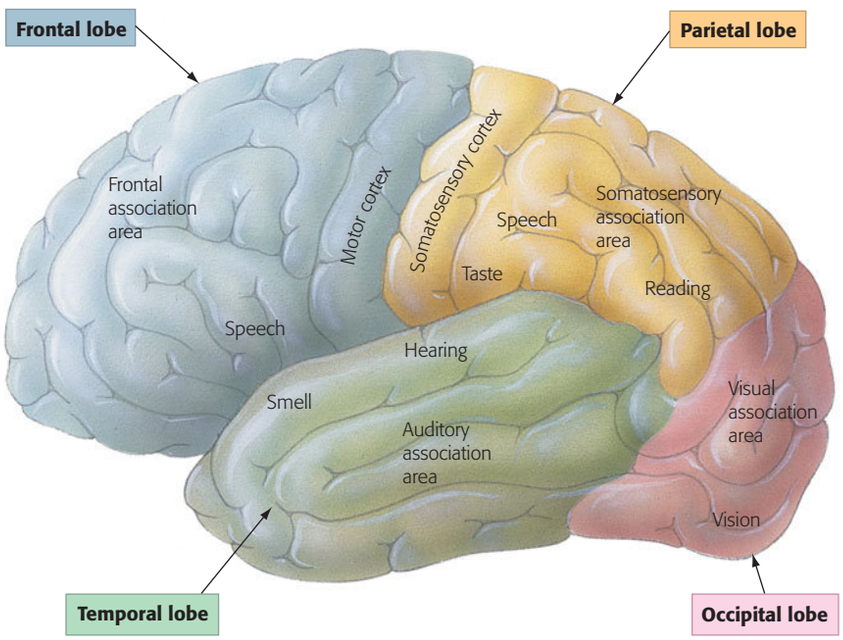
Like the rest of the cerebrum, the cerebral cortex is divided into right and left sides, connected by the corpus callosum. Because the nerve fibers from the cerebral cortex cross in the medulla oblongata, each hemisphere (right and left) receives information from and controls the movement of the opposite side of the body.

Each side of the cerebral cortex has four lobes, each named for a nearby skull bone: the frontal, parietal, temporal, and occipital lobes (represented by different colors in Figure 27.12). Researchers have identified a number of functional areas within each lobe. One region of the frontal lobe, for example, called the motor cortex, functions mainly in sending commands to skeletal muscles. The cerebral cortex also has centers that receive and begin processing sensory information such as taste, vision, hearing, and smell.

Making up most of our cerebral cortex are various **association areas**. These are the sites of higher mental activities—roughly, what we call thinking. A large association area in the frontal lobe uses varied inputs from many other areas of the brain to evaluate consequences, make considered judgments, and plan for the future. Language results from some extremely complex interactions among several association areas. For instance, the parietal lobe has association areas for reading and speech. These areas receive visual information (the appearance of words on a page) from the vision centers. Then, if the words are to be spoken aloud, the information is arranged into speech patterns and passed to a speech center in the frontal lobe, which signals the motor cortex to move the tongue, lips, and other muscles to form words.

You may have heard people say that they are "left-brained" or "right-brained." In a phenomenon known as lateralization, areas in the two hemispheres become specialized for different functions.

▼ **Figure 27.12 Functional areas of the cerebrum's left hemisphere.** This figure identifies the main functional areas in the brain's left cerebral hemisphere, which is divided into four lobes.



In most people, the left hemisphere becomes most adept at language, logic, and mathematical operations. The right hemisphere is stronger at spatial relations, pattern and face recognition, and nonverbal thinking. In about 10% of us, however, the roles of the left and right hemispheres are reversed or the roles are more alike.

Brain Trauma

Interestingly, evidence from brain surgery patients indicates that patterns of lateralization are not fixed. One of the most radical surgical alterations of the brain is hemispherectomy—the removal of almost one-half of the brain **(Figure 27.13)**. This procedure is performed to alleviate severe seizure disorders that originate from one of the hemispheres as a result of illness, abnormal development, or stroke. Incredibly, with just half a brain, hemispherectomy patients recover quickly, often leaving the hospital within a few weeks. Although the side of the body opposite the surgery always has partial paralysis, hemispherectomy patients have undiminished intellectual capacities. Higher brain functions that previously originated from the missing half of the brain begin to be controlled by the opposite side. Recovery after hemispherectomy is a striking example of the brain's remarkable ability to adapt.

Can a person survive with just half a brain?

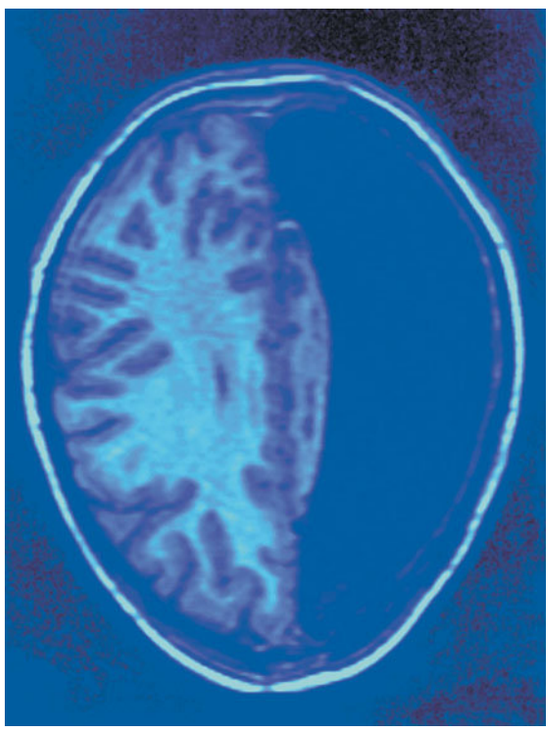
Neurologists sometimes gain insight into how the brain works from people who have suffered brain trauma. The first well-publicized case of this type involved a man named Phineas Gage. In 1848, while working in Vermont as a railroad construction foreman, Gage accidentally exploded a dynamite charge that propelled a 3-foot-long spike through his head. The 13-pound steel rod entered his left cheek and traveled upward behind his left eye and out the top of his skull, landing several yards away. Incredibly, Gage walked away from the accident and appeared to be able to think normally. However, his associates soon noticed drastic changes in his personality, with a new propensity for meanness and vulgarity and an inability to control his behavior. Gage's doctor observed these changes as well but was unable to explain them, given the limited knowledge of the brain at that time. Luckily, the doctor preserved Gage's skull and the spike, allowing a group of researchers in 1994 to produce a computer model of the injury **(Figure 27.14)**. The modern analysis offered an explanation for Gage's bizarre behavior: The rod had pierced both frontal lobes of his brain. People with these sorts of injuries often exhibit irrational decision making and difficulty processing emotions. The link between the frontal lobes and personality continues to be an active area of research. ☑

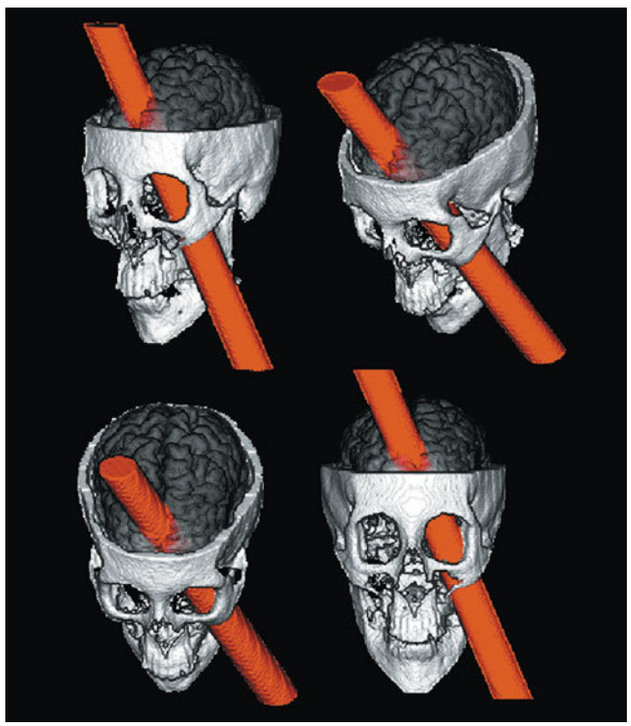
☑ CHECKPOINT

The largest and most sophistical part of your brain is the _____. It is divided into two hemispheres connected by the _____. Its surface, called the _____, accounts for most of your brain's mass and is responsible for most distinctively human traits such as language.

Answer: *cerebrum; corpus callosum; cerebral cortex*

▼ **Figure 27.13 Hemispherectomy.** This top-down X-ray view shows the skull and brain of a hemispherectomy patient after surgery.





◄ **Figure 27.14 Phineas Gage's accident.** A 1994 computer simulation of an 1848 injury to railroad worker Phineas Gage suggested that the spike that passed through his skull (shown as a red cylinder in the figure) might have damaged both frontal lobes of his brain. Such an injury could account for Gage's personality changes after the accident.

Neurological Disorders

In addition to trauma, various neurological disorders (diseases of the nervous system) can also affect brain function. Nearly 20 million American adults, about two-thirds of them women, are affected by depression. Two broad forms of depressive illness have been identified: major depression and bipolar disorder. People with **major depression** may experience persistent sadness, loss of interest in pleasurable activities, changes in body weight and sleep patterns, loss of energy, and suicidal thoughts. While all of us feel sad from time to time, major depression is extreme and more persistent, leaving the sufferer unable to live a normal life. If left untreated, symptoms may become more frequent and severe over time.

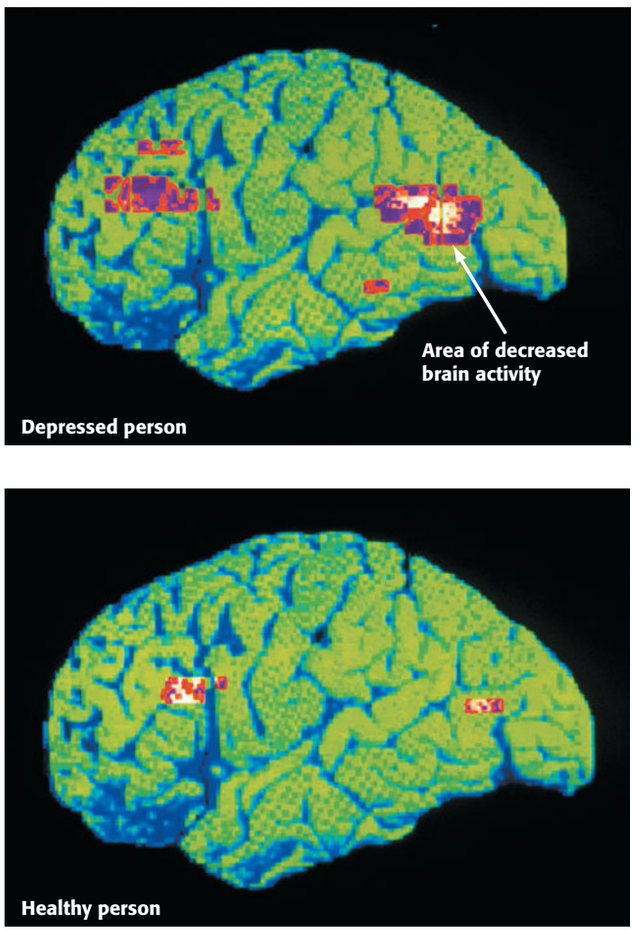
Bipolar disorder, or manic-depressive disorder, involves extreme mood swings. The manic phase is characterized by high self-esteem, increased energy, a flood of thoughts and ideas, and extreme talkativeness, as well as behaviors that often court disaster, such as increased risk taking, promiscuity, and reckless spending. In its milder forms, this phase is sometimes associated with great creativity, and some well-known musicians, artists, and literary figures with bipolar disorder (including Beethoven, Van Gogh, and Hemingway) have had periods of intense output during their manic phases. The depressive phase is marked by sleep disturbances, feelings of worthlessness, and decreased ability to experience interest and pleasure.

In recent years, researchers have begun to examine how the brain's physiology is involved in depression **(Figure 27.15)**. Many depressed people have a low level of serotonin. For this reason, serotonin is the target of the most commonly prescribed class of antidepressant medications, the selective serotonin reuptake inhibitors (SSRIs), including fluoxetine (Prozac), paroxetine (Paxil), and sertraline (Zoloft). These drugs block the reuptake of neurotransmitter at synapses (see step 6 in Figure 27.5), increasing the amount of time that serotonin is available to stimulate neurons in the brain.

How do antidepressant medications work?

Alzheimer's disease is a form of mental deterioration, or dementia, characterized by confusion, memory loss, and a variety of other symptoms. Its incidence is usually age related, rising from about 10% at age 65 to about 35% at age 85. The disease is progressive; patients gradually become less able to function and eventually need to be dressed, bathed, and fed by others. There are also personality changes, almost always for the worse. Patients often lose their ability to recognize people, even family members, and may treat them with suspicion and hostility. At present, a firm diagnosis of Alzheimer's disease is difficult to make while the patient is alive because it is one of several forms of dementia.

Unraveling how networks of neurons in the brain produce thoughts and emotions, store and retrieve memories, and control the body's internal environment is one of the most challenging and engaging aspects of modern biology. In the next section, we'll examine how the brain receives information from the environment via the sense organs. ☑



▲ **Figure 27.15 Brain activity in a depressed person and a healthy person.** The purple and pink colors in these computer images indicate areas of low brain activity. Notice that the brain of the depressed person shows decreased activity in certain areas of the brain.

☑ CHECKPOINT

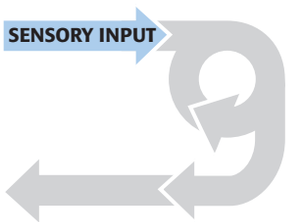
What are the two primary categories of depression?

Answer: major depression and bipolar disorder

The Senses

In this section, we'll focus on the human body's sensory structures. To begin, we'll examine how these structures gather information and pass it on to the central nervous system (CNS). After that, we'll take a closer look at two of the human senses, vision and hearing.

Sensory Input



Sensory input is the process of using receptors to sense the environment and send information about it to the CNS to be integrated and acted upon. Sensory receptors, such as the sensory cells in your eyes or the taste buds of your tongue, are tuned to the condition of both the external world and internal organs. Sensory receptors detect stimuli such as chemicals, light, sounds, cold, heat, and touch. The sensory receptors in your eyes, for instance, detect light energy; those in your taste buds detect chemicals dissolved in saliva. The sensory receptor's job is completed when it sends information to the CNS by triggering action potentials.

What exactly do we mean when we say that a sensory receptor detects a stimulus? In stimulus detection, the receptor cell converts one type of signal (the stimulus) to an electrical signal. This conversion of the signal, called **sensory transduction**, occurs as a change in the membrane potential of the receptor cell.

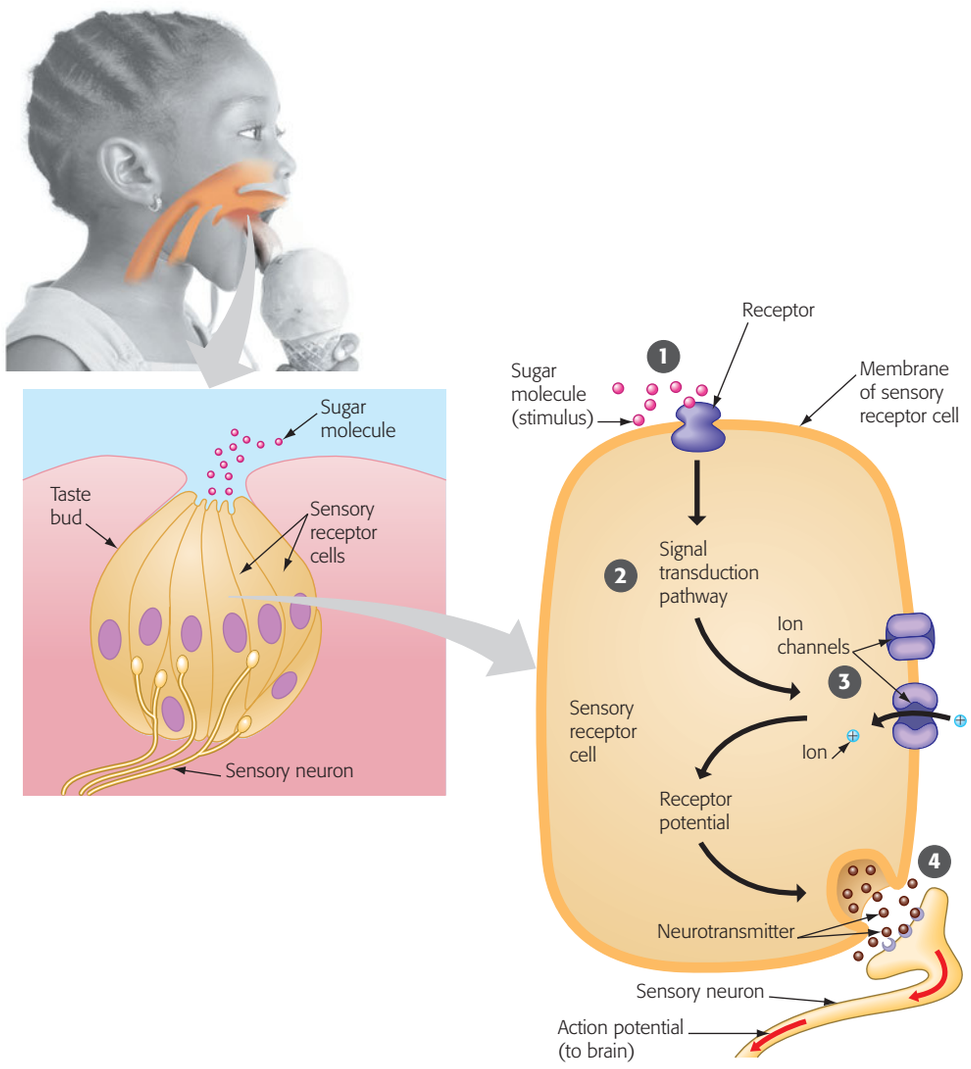
Sensory Transduction

As an example of sensory transduction, Figure 27.16 shows sensory receptors in a taste bud detecting sugar molecules. 1 When the sugar molecules (●) first come into contact with the taste bud, they bind to membrane receptors of the sensory receptor cells. 2 This binding triggers a signal transduction pathway that 3 causes some ion channels in the membrane to close and others to open. Changes in the flow of ions (⊕) alter the membrane potential. This change in membrane potential is called the **receptor potential**. In contrast to action potentials, which are all-or-none phenomena, receptor potentials vary in intensity; the stronger the stimulus, the stronger the receptor potential.

Once a receptor cell converts a stimulus to a receptor potential, this potential usually results in signals being sent to the CNS. In Figure 27.16, 4 each receptor cell forms a synapse with a sensory neuron. When there are enough sugar molecules, a strong receptor potential is triggered. This receptor potential makes the receptor cell release enough neurotransmitter (●) to increase the rate of action potential generation in the sensory neuron. The brain interprets the intensity of the stimulus from the rate at which it receives action potentials. It gains additional information about stimulus intensity by keeping track of how many sensory neurons it receives signals from.

There is an important qualification to what we have just said about stimulus intensity. Have you ever noticed how an odor that is strong at first seems to fade with time, even when you know the smell is still there? Or how the water in a pool is shockingly cold when you first jump in, but then you get used to it? This effect is called **sensory adaptation**, the tendency of some sensory receptors to become less sensitive when they are stimulated

Figure 27.16 Sensory transduction in a human taste bud.



repeatedly. When receptors become less sensitive, they trigger fewer action potentials, causing the brain to receive fewer stimuli. Sensory adaptation keeps the body from continuously reacting to normal background stimuli. Without it, our nervous system would become overloaded with useless information.

Types of Sensory Receptors

Based on the type of signals to which they respond, we can group sensory receptors into five general categories: pain receptors, thermoreceptors (sensors for heat and cold), mechanoreceptors (sensors for touch, pressure, motion, and sound), chemoreceptors (sensors for chemicals), and electromagnetic receptors (sensors for energy such as light and electricity). These five types of receptors work in various combinations to produce the five human senses.

Figure 27.17, showing a section of human skin, reveals why the surface of our body is sensitive to such a variety of stimuli. Our skin contains pain receptors (labeled in red in the figure), thermoreceptors (blue), and mechanoreceptors (green). Each of these receptors is a modified dendrite of a sensory neuron. Each receptor is capable of recognizing a stimulus and responding to it by sending an action potential to the CNS. In other words, each receptor serves as both a receptor cell and a sensory neuron.

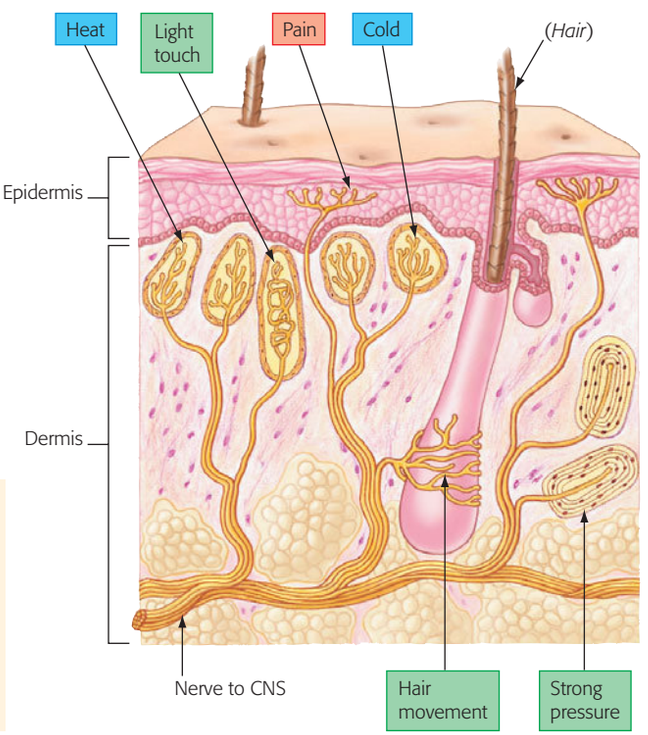
All parts of the human body except the brain have pain receptors. Pain is important because it often indicates danger and usually makes an animal withdraw to safety. Pain can also make us aware of injury or disease. **Pain receptors** may respond to excessive heat or pressure or to chemicals released from damaged or inflamed tissues. Prostaglandins are local regulators that increase pain by sensitizing pain receptors. Aspirin and ibuprofen reduce pain by inhibiting prostaglandin synthesis.

Thermoreceptors in the skin detect either heat or cold. Other temperature sensors located deep in the body monitor the temperature of the blood. The body's major thermostat is the hypothalamus. Receiving action potentials both from surface sensors and from deep sensors, the hypothalamus keeps a mammal's or bird's body temperature within a narrow range (see Figure 21.14).

Mechanoreceptors are highly diverse. Different types are stimulated by different forms of mechanical energy, such as touch and pressure, stretching, motion, and sound. All these forces produce their effects by bending or stretching the plasma membrane of a receptor cell. When the membrane changes shape, it becomes more permeable to positive ions, and the mechanical energy of the stimulus is transduced into a receptor potential. One example of a mechanoreceptor is the touch receptor at the base of a cat's whisker. These receptors are extremely sensitive and enable the animal to detect objects by touch in the dark. The elephants you learned about in the Biology and Society section provide another example; they detect seismic waves through mechanoreceptors in their feet and trunk.

Chemoreceptors include the sensory cells in your nose and taste buds, which are attuned to chemicals in the external environment, as well as some internal receptors that detect chemicals in your body's internal environment. Internal chemoreceptors include sensors in your arteries that monitor your blood, with some sensors detecting changes in pH and others detecting changes in O_2 concentration. In all types of chemoreceptors, a receptor cell develops receptor potentials in response to chemicals dissolved in fluid such as blood or saliva.

Electromagnetic receptors are sensitive to energy of various wavelengths, which takes such forms as magnetism and light. For example, **photoreceptors** detect the electromagnetic energy of light. In the next section, we'll focus on one specific organ that uses photoreceptors: the human eye. ☑



► **Figure 27.17**
Sensory receptors in the human skin. Your skin is sensitive to a wide variety of stimuli because it contains a wide variety of receptors.

☑ CHECKPOINT

What is meant by sensory transduction?

Answer: the conversion of a stimulus detected by a sensory receptor to an electrical signal (a receptor potential)

Vision

The human eye is a remarkable sense organ, able to detect a multitude of colors, form images of objects both near and far, and respond to minute amounts of light energy. In this section, you'll learn about the structure of the human eye and how it processes images. You'll also learn why vision problems occur and how they can be corrected.

Structure of the Human Eye

The outer surface of the human eyeball is a tough, whitish layer of connective tissue called the **sclera** (Figure 27.18). At the front of the eye, the sclera becomes the transparent **cornea**. The sclera surrounds a pigmented layer called the choroid. At the front of the eye, the choroid forms the **iris**, which gives the eye its color. The opening in the center of the iris is called the **pupil**. Behind the pupil is the disklike **lens**, which is held in position by ligaments. At the back of the eyeball is the **retina**, a layer of tissue just inside the choroid that contains photoreceptor cells. The **optic nerve** connects the retina with the brain. There are no photoreceptor cells in the part of the retina where the optic nerve passes through the back of the eye. We cannot detect light that is focused on this "blind spot," but having two eyes with overlapping fields of view enables us to perceive uninterrupted images.

Two fluid-filled chambers make up the bulk of the eye. The large chamber behind the lens is filled with jellylike **vitreous humor**. The much smaller chamber in front of the lens contains a thinner fluid called the **aqueous humor**. The humors help maintain the shape of the eyeball. In addition, the aqueous humor supplies nutrients and oxygen to the lens, iris, and cornea and carries off wastes. Blockage of the ducts that drain this fluid can cause glaucoma, increased pressure inside the eye that may lead to blindness. If diagnosed early, glaucoma can be treated with medications that increase the circulation of the aqueous humor.

A thin mucous membrane called the conjunctiva helps keep the outside of the eye moist. The conjunctiva lines the inner surface of the eyelids and folds back over the white of the eye (but not the cornea). An infection or allergic reaction may cause inflammation of the conjuctiva, a condition called conjunctivitis or "pink eye." Bacterial conjuctivitis usually clears up with antibiotic eyedrops. Viral conjunctivitis usually clears up on its own, although it is very contagious, especially among young children.

A gland above the eye secretes tears, a dilute salt solution that is spread across the eyeball by blinking and that drains into ducts leading into the nasal cavities. This fluid cleanses and moistens the eye surface. Excess secretion, in response to eye irritation or strong emotions, causes tears to spill over the eyelid and fill the nasal cavities, producing a runny nose.

Function of the Human Eye

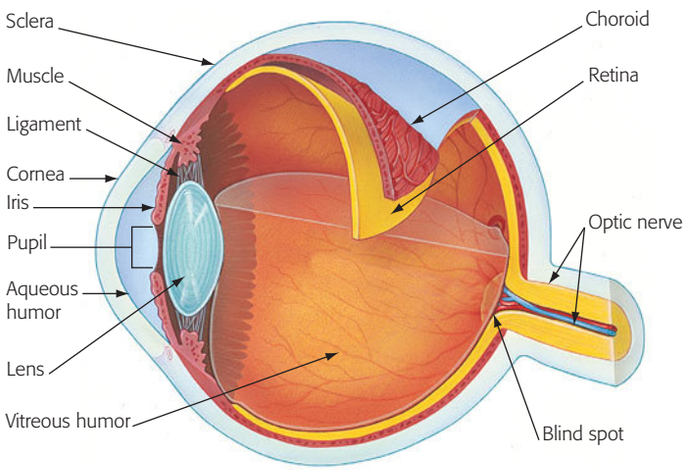
The cornea lets light into the eye and also helps focus light. The muscles of the iris regulate the size of the pupil, controlling the amount of light that enters. After going through the pupil, light passes through the lens. The lens focuses light onto the retina by bending light rays. Focusing is accomplished through a change in the shape of the lens (Figure 27.19). The thicker the lens, the more sharply it bends light. The shape of the lens is controlled by the muscles attached to the choroid. When the eye focuses on a nearby object, these muscles contract, pulling the choroid layer of the eye inward toward the pupil. This makes the ligaments that suspend the lens slacken. With this reduced tension, the elastic lens becomes thicker and rounder. When the eye focuses on a distant object, the muscles controlling the lens relax, putting tension on the ligaments and flattening the lens. ☑

☑ CHECKPOINT

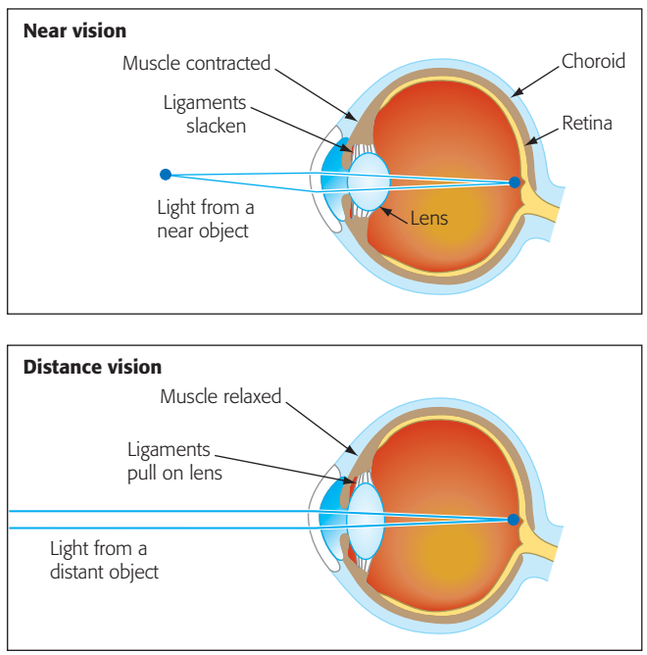
Arrange the following eye parts into the correct sequence encountered by photons of light traveling into the eye: pupil, retina, cornea, lens, vitreous humor, aqueous humor.

Answer: cornea → aqueous humor → pupil → lens → vitreous humor → retina

▼ Figure 27.18 The human eye.



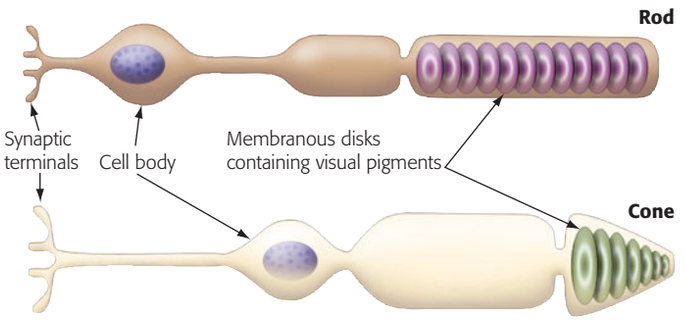
► Figure 27.19 How the lens of the eye focuses light. When viewing a nearby object (top), the lens becomes thicker and rounder and focuses the image on the retina. When viewing a distant object (bottom), the lens becomes flattened, and the image is again focused on the retina.



Photoreceptors

The human retina contains two types of photoreceptors named for their shapes (Figure 27.20). **Rods** are extremely sensitive to light and enable us to see in dim light, though only in shades of gray. **Cones** are stimulated by bright light and can distinguish color, but they contribute little to night vision.

In humans, rods are found in greatest density at the outer edges of the retina and are completely absent from the center. In contrast, the retina's center of focus contains a high concentration of cones (Figure 27.21). If you look directly at a dim star in the night sky, the star is hard to see. Looking just to the side, however, makes your lens focus the starlight onto the parts of the retina with the most rods, and you can see the star. By contrast, you achieve your sharpest day vision by looking straight at the object of interest. Some birds, such as hawks, have ten times more cones than we do, enabling them to spot small prey from high altitudes.



▲ **Figure 27.20 Photoreceptor cells.** Your eyes contain many more rods than cones.

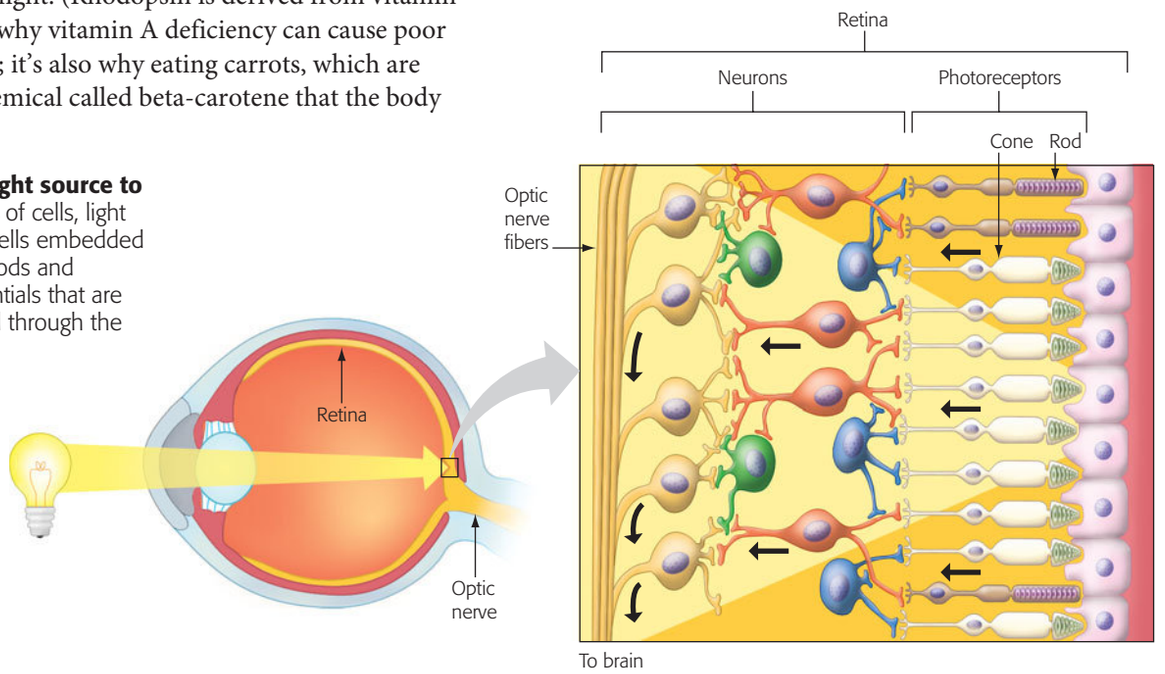
How do rods and cones detect light? As Figure 27.20 shows, each rod and cone includes an array of disks containing light-absorbing visual pigments. Rods contain a visual pigment called rhodopsin, which can absorb dim light. (Rhodopsin is derived from vitamin A, which is why vitamin A deficiency can cause poor night vision; it's also why eating carrots, which are rich in a chemical called beta-carotene that the body converts to vitamin A, helps prevent vision loss.) Cones contain visual pigments called photopsins, which absorb colored, bright light. We have three types of cones, each containing a different type of photopsin. These cells are called blue cones, green cones, and red cones, referring to the colors absorbed best by their photopsin. We can perceive a great number of colors because the light from each particular color triggers a unique pattern of stimulation among the three types of cones. Colorblindness results from a deficiency in one or more types of cones.

Like all receptor cells, rods and cones convert a stimulus to an electrical signal (see Figure 27.21). When rhodopsin and photopsin absorb light, they change chemically, and the change alters the permeability of the cell's membrane. The resulting receptor potentials trigger a complex integration process that begins in the retina. Other retinal neurons start to integrate the receptor potentials and in doing so produce action potentials. These action potentials travel along the optic nerve, carrying the partly integrated information into the brain. Three-dimensional perceptions (what we actually see) result from further integration in several processing centers of the cerebral cortex. ☑

☑ CHECKPOINT

Explain why our night vision is mostly in shades of gray rather than in color.

Answer: Rods are more sensitive than cones to dim light, and thus the low light intensity at night stimulates far more rods than color-sensing cones.



► **Figure 27.21 The vision pathway from light source to optic nerve.** After passing through many layers of cells, light entering the human eye strikes photoreceptor cells embedded in the back of the retina. Once stimulated, the rods and cones convert the light energy to receptor potentials that are integrated by other neurons and communicated through the optic nerve as action potentials to the brain.

Vision Problems and Corrections

When you have your vision tested, you view a chart that shows how various letters of the alphabet would look at various distances. You are asked to read different rows of letters using one eye at a time. If you can read the row that is sized for legibility at a distance of 20 feet with each of your eyes, you have normal (20/20) vision in each eye. Suppose you find out that you have 20/10 vision. This is better than normal; you can read letters from a distance of 20 feet that a person with 20/20 vision can only read at 10 feet. However, someone with 20/50 vision has worse than normal vision. He or she must stand at a distance of 20 feet to read what a person with normal vision can read at 50 feet.

Three of the most common visual problems are nearsightedness, farsightedness, and astigmatism. All three are focusing problems, easily corrected with artificial lenses. People with **nearsightedness** cannot focus well on distant objects, although they can see well at short distances (the condition is named for the type of vision that is *unimpaired*). A nearsighted eyeball **(Figure 27.22a)** is longer than normal. The lens cannot flatten enough to compensate, and it focuses distant objects in front of the retina instead of on it. Nearsightedness (also known as myopia) is corrected by glasses or contact lenses that are thinner in the middle than at the outside edge. The corrective lenses make the light rays from distant objects diverge slightly as they enter the eye. The image formed by the lens in the eye is then focused at the correct point.

How does LASIK surgery work?

Farsightedness (also known as hyperopia) occurs when the eyeball is shorter than normal, causing the lens to focus images behind the retina **(Figure 27.22b)**. Farsighted people see distant objects normally, but they can't focus on close objects. Corrective lenses that are thicker in the middle than at the outside edge compensate for farsightedness by making light rays from nearby objects converge slightly before they enter the eye.

Astigmatism is blurred vision caused by a misshapen lens or cornea. Any such distortion makes light rays converge unevenly and not focus at any one point on the retina. Lenses that correct astigmatism are asymmetrical in a way that compensates for the asymmetry in the eye.

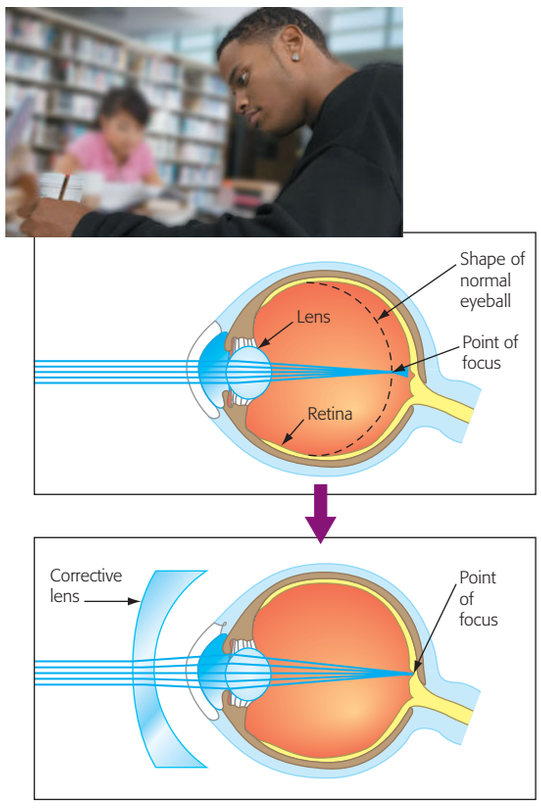
Surgical procedures are an option for treating vision disorders. In laser-assisted in situ keratomileusis (LASIK), a laser is used to reshape the cornea and change its focusing ability. More than 1 million LASIK procedures are performed each year to correct a variety of vision problems. ☑

☑ CHECKPOINT

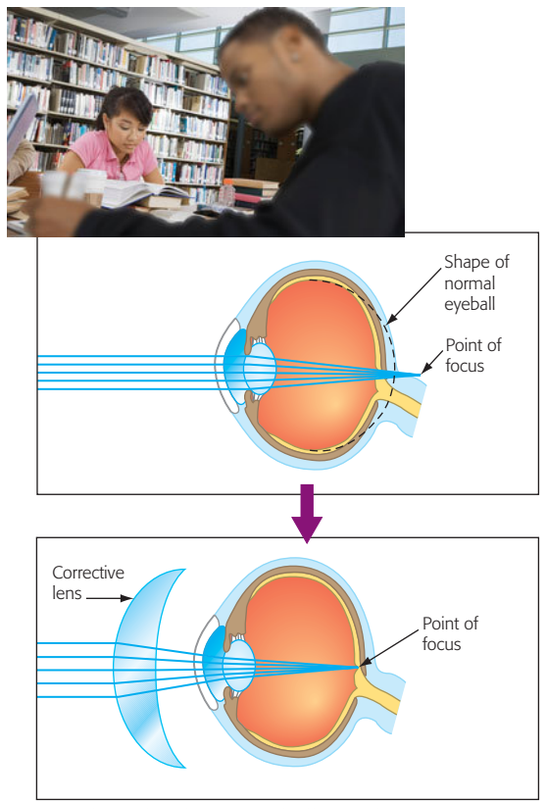
A person who requires reading glasses has a case of _____.

Answer: farsightedness (hyperopia)

► **Figure 27.22 A nearsighted eye and a farsighted eye.** Corrective lenses help vision problems by focusing the image exactly on the retina.



(a) A nearsighted eye (eyeball too long). Nearsightedness is corrected by lenses that are thinner toward the middle.



(b) A farsighted eye (eyeball too short). Farsightedness is corrected by lenses that are thicker in the middle.

Hearing

Although the human ear is less sensitive than that of many other animals, it is capable of hearing a great range of auditory signals. In this section, we'll examine the structure and function of the human ear.

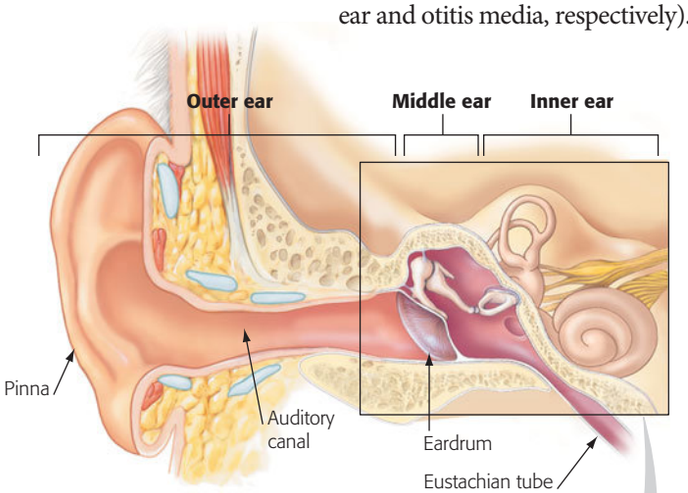
Structure of the Human Ear

The ear is composed of three regions: the outer ear, the middle ear, and the inner ear (Figure 27.23a). The **outer ear** consists of the flap-like **pinna**—the bendable structure we commonly refer to as our "ear"—and the **auditory canal**. A sheet of tissue called the **eardrum** separates the outer ear from the middle ear. Both the outer ear and middle ear are common sites of childhood infections (called swimmer's ear and otitis media, respectively).

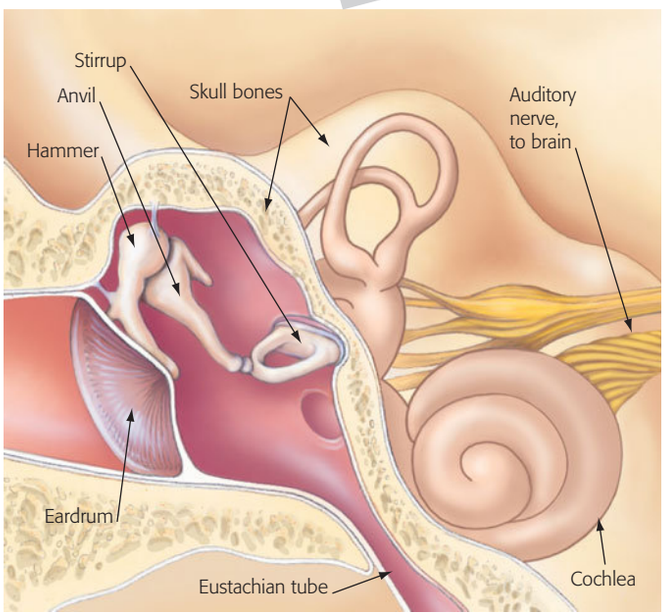
The **middle ear** contains three small bones (Figure 27.23b): the hammer (more formally, the malleus), the anvil (incus), and the stirrup (stapes). (Interestingly, the hammer bone of elephants is unusually large, perhaps giving it greater ability to amplify subtle seismic vibrations.) The stirrup is connected to the inner ear through an opening in the skull bone. The **Eustachian tube** conducts air between the middle ear and the back of the throat, allowing air pressure to stay equal on either side of the eardrum. This tube is what enables you to move air in or out to equalize pressure ("pop" your ears) when changing altitude rapidly in an airplane or diving underwater.

The **inner ear** consists of fluid-filled channels in the bones of the skull. One of the channels, the **cochlea**, is a long, coiled tube. Our actual hearing organ, the organ of Corti, is located within a fluid-filled canal inside the cochlea (Figure 27.24). The organ of Corti consists of an array of hair cells embedded in a structure called the basilar membrane. The hair cells are the receptor cells of the ear. Notice that they project into the fluid and that the tips of most are in contact with the overlying jelly-like membrane. Sensory neurons at the base of the hair cells connect to the auditory nerve, which connects in turn to the brain.

▼ Figure 27.23 An overview of the human ear.

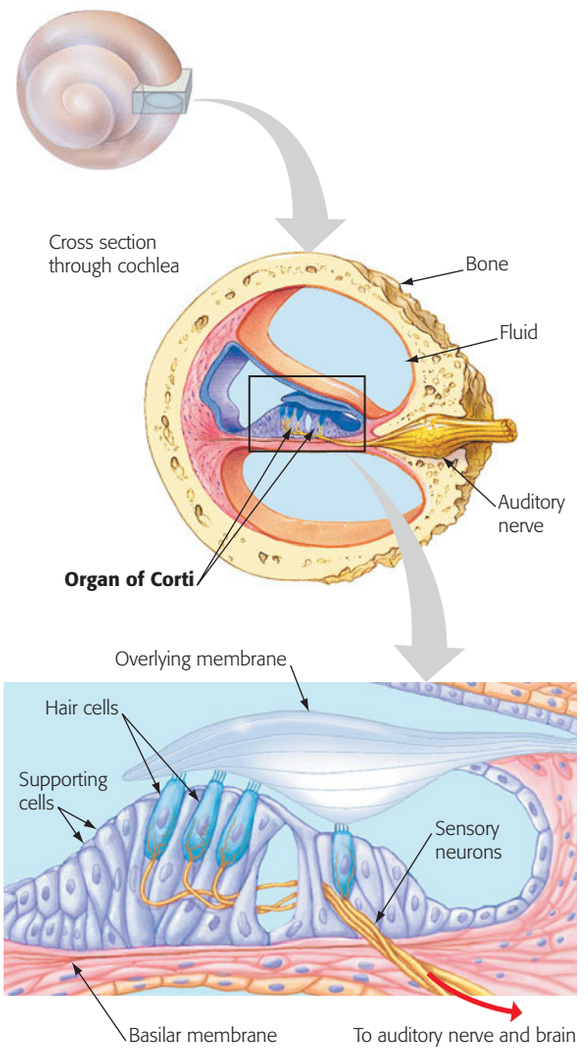


(a) Ear structure. The human ear is divided into three regions: the outer, middle, and inner ears.



(b) The middle and inner ears. The bones of the middle ear are connected to the fluid-filled channels of the cochlea in the inner ear.

▼ Figure 27.24 The organ of Corti. The organ of Corti is located within a fluid-filled canal inside the cochlea. Receptor cells (hair cells) connect to sensory neurons, which in turn connect to the auditory nerve and the brain.

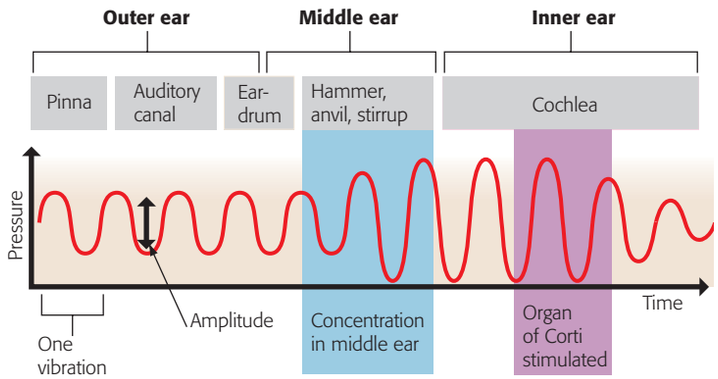


Function of the Human Ear

Now let's see how the parts of the ear function in hearing. As indicated in **Figure 27.25**, a vibrating object such as a plucked guitar string creates sound waves in the surrounding air, represented by the up-and-down waves in the figure. The pinna and the auditory canal collect these waves and channel them to the eardrum. The waves make your eardrum vibrate with the same frequency as the sound. (Frequency is the number of vibrations per second.) From the eardrum, the vibrations are concentrated as they pass through the hammer, anvil, and stirrup in the middle ear. The stirrup transmits the vibrations to the inner ear, producing pressure waves in the fluid within the cochlea.



▼ **Figure 27.25 The route of sound waves through the ear.** This figure traces the path of a sound stimulus as it passes from the environment to the brain.



As a pressure wave passes through the cochlea, it makes the basilar membrane vibrate. Vibration of the basilar membrane makes the hairlike projections on the hair cells alternately brush against and draw away from the overlying membrane. When a hair cell's projections are bent, ion channels in its plasma membrane open, and positive ions enter the cell. As a result, the hair cell develops a receptor potential and releases neurotransmitter molecules at its synapse with a sensory neuron. In turn, the sensory neuron sends action potentials through the auditory nerve to the brain.

How is the volume of a sound determined? The higher the volume (loudness) of sound, the greater the amplitude (height) of the pressure wave it generates. In the ear, the greater the amplitude, the more vigorous the vibrations of fluid in the cochlea, the more pronounced the bending of the hair cells, and the more action potentials generated in the sensory neurons.

Hearing Problems

Deafness, the loss of hearing, can be caused by the inability to conduct sounds, resulting from middle-ear infections, a ruptured eardrum, or stiffening of the middle-ear bones (a common age-related problem). Deafness can also result from damage to receptor cells or neurons. Because few parts of our anatomy are more delicate than the organ of Corti, deafness is often progressive and permanent. In recent years, however, many deaf people have received cochlear implants, electronic devices that convert sounds to electrical impulses that stimulate the auditory nerve directly.

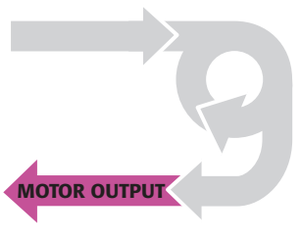
Frequent or prolonged exposure to very loud sounds can damage or destroy the hair cells of the inner ear. For example, you may have noticed that a few hours in a very loud environment leaves you with ringing or buzzing sounds in your ears, a condition called tinnitus. Ear plugs can provide protection. ☑

☑ CHECKPOINT

How does the ear convert sound waves in the air to pressure waves in the fluid of the inner ear?

Answer: Sound waves in the air cause the eardrum to vibrate. The small bones attached to the inside of the eardrum transmit vibrations to the fluid of the inner ear, producing pressure waves.

Locomotor Systems



So far, we've seen how the body senses the environment via sensory receptors and integrates this information within the central nervous system. In this section, we'll consider how the body couples stimulus to locomotor response (movement), thereby completing the neural circuit.

Movement is one of the most distinctive features of animals. Whether an animal walks or runs on two, four, or six legs or more, swims, crawls, flies, or sits in one place and only moves its mouthparts, an interplay of organ systems is responsible for its movement. The nervous system plays a key role in issuing commands to the muscular system. The muscular system exerts the force that actually makes an animal or its parts move. But the force exerted by muscles produces movement only when it is applied against a firm structure. In vertebrates, this structure is the skeletal system. In this section, we focus on the human skeleton and muscles and the movement their interactions produce.

The Skeletal System

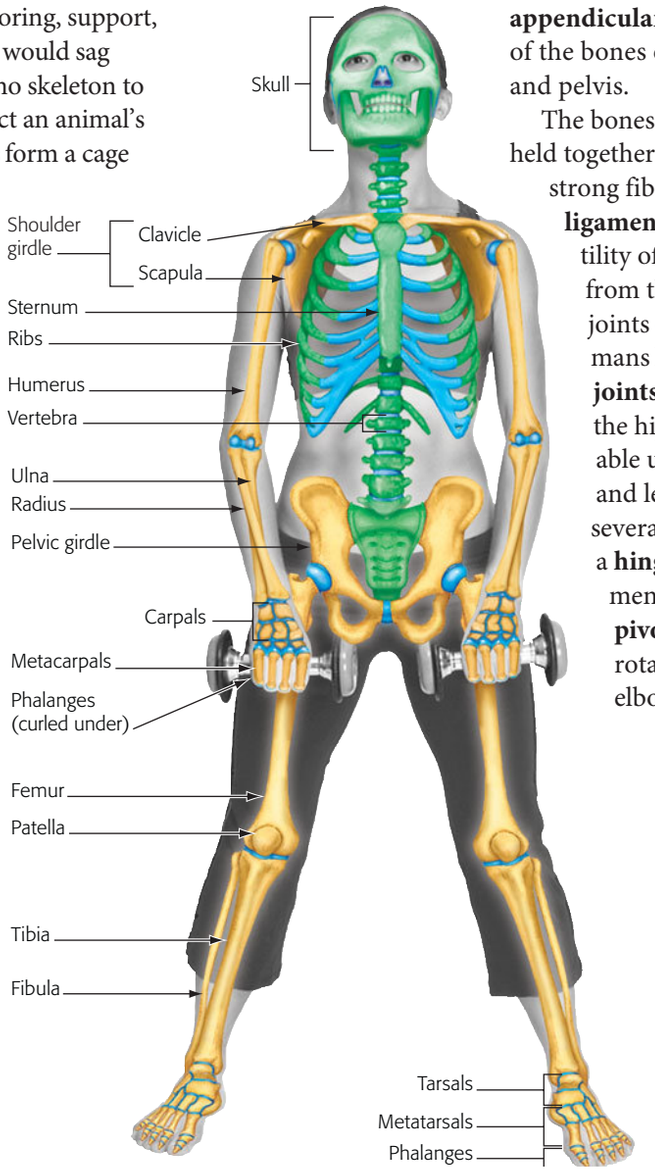
The **skeletal system** provides anchoring, support, and protection. Most land animals would sag from their own weight if they had no skeleton to support them. Skeletons also protect an animal's soft organs. For example, your ribs form a cage around your heart and lungs. In this section, we'll discuss the human skeleton: its organization, its structure, and some of the problems that may arise with it.

Organization of the Human Skeleton

Humans, like all vertebrates, have an **endoskeleton**—hard supporting elements situated among soft tissues. The human endoskeleton is a combination of cartilage and the 206 bones that make up the skeletal system (Figure 27.26); the cartilage provides flexibility in certain areas.

The human skeleton is organized into two basic units: the axial skeleton and the appendicular skeleton. The **axial skeleton** supports the axis, or trunk, of the body and includes the skull, enclosing and protecting the brain; the vertebrae of the spinal column, enclosing the spinal cord; and the ribs. The **appendicular skeleton** is made up of the bones of the limbs, shoulders, and pelvis.

The bones of the skeleton are held together at movable joints by strong fibrous tissues called **ligaments**. Much of the versatility of our skeleton comes from three types of movable joints (Figure 27.27). Humans have **ball-and-socket joints** in the shoulder and the hip. These joints enable us to rotate our arms and legs and move them in several planes. In the elbow, a **hinge joint** permits movement in a single plane. A **pivot joint** enables us to rotate the forearm at the elbow. ☑



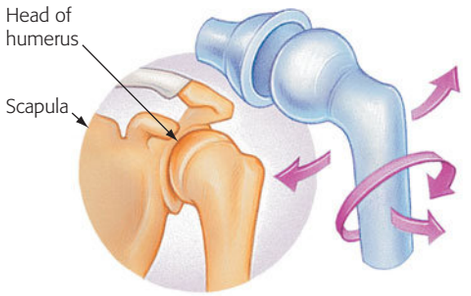
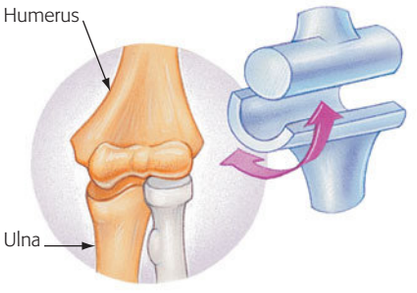
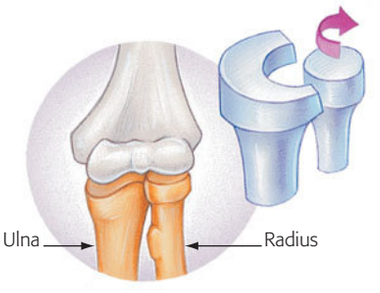
◄ **Figure 27.26 The human endoskeleton.** The human skeleton is divided into the axial skeleton (green), which supports the trunk, and the appendicular skeleton (gold), which supports the limbs. Cartilage (blue) provides flexibility at various points.

☑ CHECKPOINT

Of the following, which is not part of the axial skeleton: skull, ribs, pelvis, vertebrae?

Answer: *pelvis*

▼ **Figure 27.27 Three kinds of joints.**

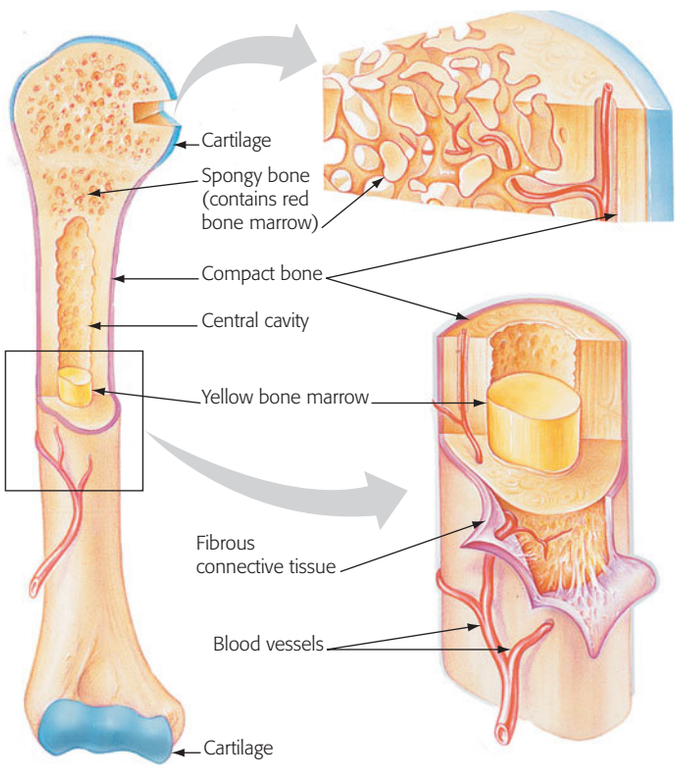
JOINTS		
Ball-and-socket (example: shoulder)	**Hinge** (example: elbow flexing)	**Pivot** (example: elbow rotation)
		

The Structure of Bones

Although they may appear dry and dead, bones are complex organs consisting of several kinds of living tissues. You can get a sense of some of a bone's complexity from the cutaway view of the human humerus (the upper arm bone) shown in **Figure 27.28**. A sheet of fibrous connective tissue, shown in pink (most visible in the enlargement on the lower right), covers most of the outside surface. This tissue can form new bone during normal growth or in the event of a fracture. At either end of the bone is a thin sheet of cartilage (blue), also living tissue, that cushions joints, protecting the ends of bones as they move against each other. The bone itself contains cells that secrete a surrounding material, or matrix (see Figure 21.4f). Like all living tissues, bone tissues require servicing. Blood vessels course through channels in the bone, transporting nutrients and regulatory hormones to its cells and waste materials from them.

Notice that the shaft of the long bone shown in Figure 27.28 surrounds a central cavity. The central cavity contains yellow bone marrow, which is mostly stored fat brought into the bone by the blood. The ends of the bone have cavities that contain red bone marrow (not shown in the figure), a specialized tissue that produces blood cells (see Chapter 23).

▼ Figure 27.28 The structure of an arm bone.



Skeletal Diseases and Injuries

Your skeleton is quite strong and provides you with reliable support, but it is susceptible to disease and injury. **Arthritis**—inflammation of the joints—affects one out of every seven people in the United States. The most common form of arthritis occurs as a result of aging: The joints become stiff and sore and often swell as the cartilage between the bones wears down. Sometimes the bones thicken at the joints, producing crunching noises when they rub together and restricting movement. This form of arthritis is irreversible but not crippling in most cases, and moderate exercise, rest, and over-the-counter pain medications usually relieve most symptoms.

Rheumatoid arthritis is a debilitating autoimmune disease. The joints become highly inflamed, and their tissues may be destroyed by the body's immune system (see Figure 24.16). Rheumatoid arthritis usually begins between ages 40 and 50 and affects more women than men. Anti-inflammatory drugs relieve symptoms, but there is no cure.

Osteoporosis is another serious bone disorder. It is most common in women after menopause: Estrogen contributes to normal bone maintenance, and with lowered production of the hormone, bones may become thinner, more porous, and more easily broken. Insufficient exercise, smoking, diabetes mellitus, and an inadequate intake of protein and calcium may also contribute to the disease. Treatments include calcium and vitamin supplements, hormone replacement therapy, and drugs that slow bone loss or increase bone formation. Prevention of osteoporosis begins with sufficient calcium intake while bones are still increasing in density (up until about age 35). Weight-bearing exercise (walking, jogging, lifting weights) builds bone mass and is beneficial throughout life.

▼ Figure 27.29 Broken bones. These X-rays show the same set of fractured leg bones (tibia and fibula) before (left) and after they have been held together with screws and a plate (right).



Bones are rigid but not inflexible; they will bend in response to external forces. However, as many of us know from personal experience, the skeletal system has its limits. If a force is applied that exceeds a bone's capacity to bend, the result is a broken bone, or fracture. The average American will break two bones during his or her lifetime, most commonly the forearm or, for people over 75, the hip.

Treatment of a fracture involves two steps: putting the bone back into its natural shape and then immobilizing it until the body's natural bone-building cells can repair the fracture. A splint or a cast is usually sufficient to protect the area, prevent movement, and promote healing. In more severe cases, a fracture can only be repaired surgically by inserting plates, rods, and/or screws that hold the broken pieces together **(Figure 27.29)**. ☑

☑ CHECKPOINT

What two things can a young person do to help prevent osteoporosis?

Answer: ingest plenty of calcium and engage in weight-bearing exercise regularly

The Muscular System

Now that you've learned about the skeletal system, we can focus on the **muscular system**, which is made up of all the skeletal muscles in the body. **Skeletal muscles** are attached to the skeleton and produce body movement by interacting with it. **Figure 27.30** illustrates how muscles interact with bones to raise and lower the human forearm. As shown in the figure, strong fibrous tissue called **tendons** connects muscles to bones. For instance, one end of the triceps muscle is attached by tendons to bones of the shoulder. The other end is attached by a tendon to one of the bones in the forearm.

The ability to move the forearm in opposite directions requires that two muscles work as an antagonistic pair—that is, the two muscles must perform opposite tasks.

Why can't you flex your biceps and your triceps simultaneously?

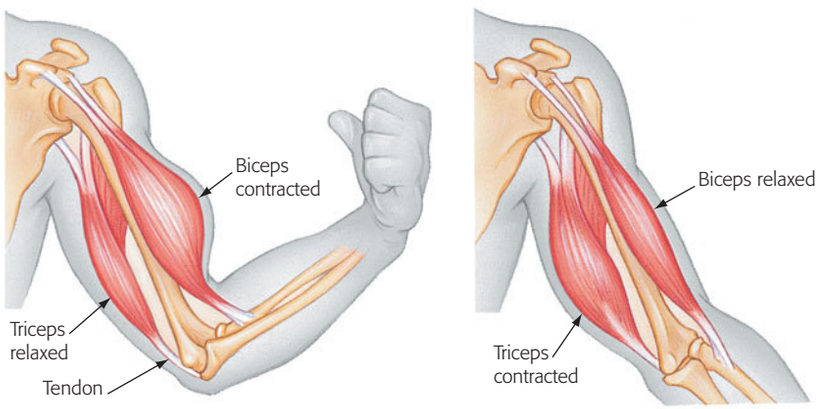
For example, contraction of the biceps muscle shortens the muscle and pulls up the forearm. The triceps muscle is the biceps's antagonist; contraction of the triceps pulls the forearm down. Notice in Figure 27.30 that when one muscle is contracted, the antagonistic (opposite) muscle is relaxed.

The Cellular Basis of Muscle Contraction

Skeletal muscle is made up of a hierarchy of smaller and smaller parallel strands. As shown at the top of **Figure 27.31**, a muscle consists of bundles of parallel muscle fibers. Each muscle fiber is a single, long cell with many nuclei. In the middle of the figure, notice that each muscle fiber is itself a bundle of smaller **myofibrils**. Skeletal muscle is also called striated (striped) muscle because the myofibrils exhibit alternating light and dark bands when viewed with a microscope. A myofibril consists of repeating units called **sarcomeres**. Structurally, a sarcomere is the region between two dark, narrow lines in the myofibril. Functionally, the sarcomere is the contractile apparatus in a myofibril—the muscle fiber's fundamental unit of action.

The micrograph and the diagram below it at the bottom of Figure 27.31 reveal the structure of a sarcomere in more detail. A myofibril is composed of regular arrangements of two kinds of filaments: **thin filaments** made primarily from the protein actin (blue in the diagram) and **thick filaments** made from the protein myosin (red).

A sarcomere contracts (shortens) when its thin filaments slide past its thick filaments. The model describing this process is known as the sliding-filament model of muscle contraction. **Figure 27.32**, a simplified



▼ Figure 27.30 Antagonistic action of muscles in the human arm. Many movements are produced through the action of two opposing muscles. In this example, contraction of the biceps muscle raises the forearm, while contraction of the triceps muscle lowers the forearm.

▼ Figure 27.31 The contractile apparatus of skeletal muscle.

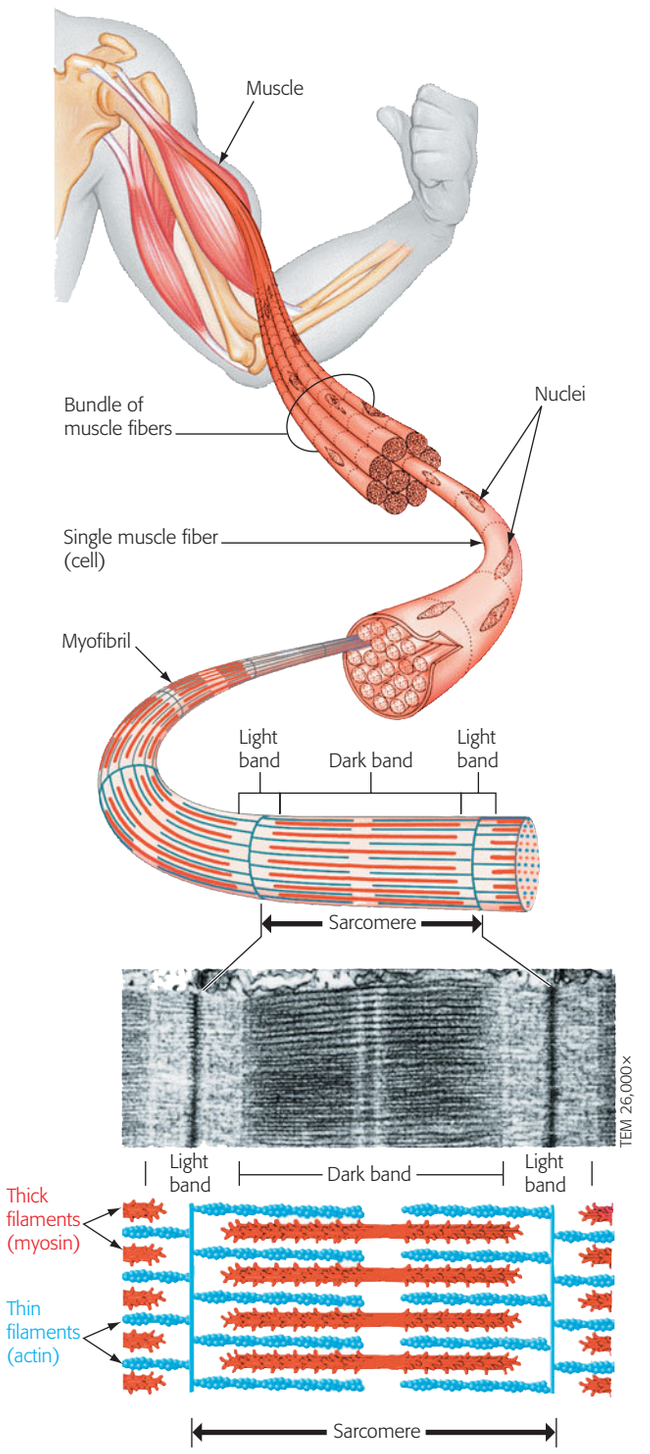


Figure 27.32 The sliding-filament model of muscle contraction. Notice that the lengths of the thick and thin filaments do not change; the two types of filaments merely slide past each other to overlap.

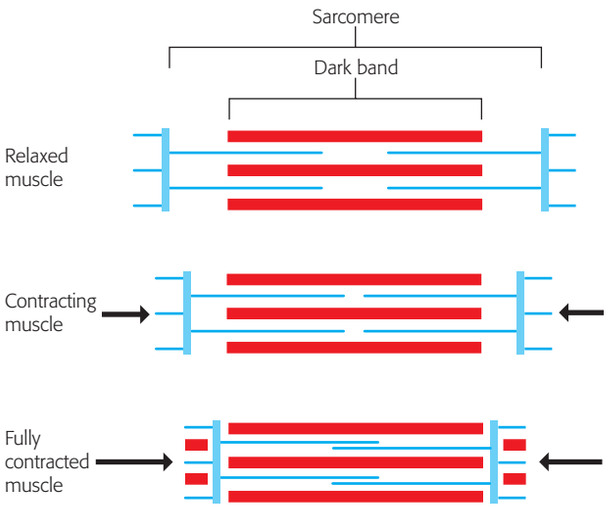
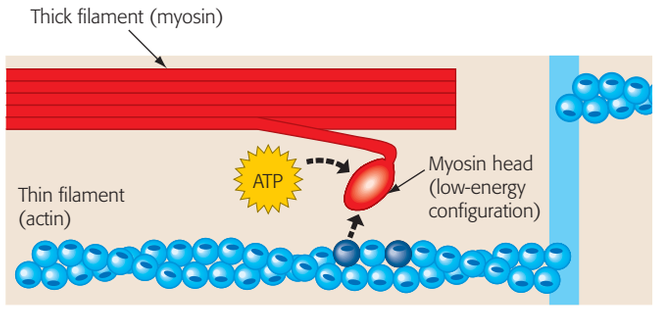


diagram of this model, shows a sarcomere in a relaxed muscle, a contracting muscle, and a fully contracted muscle. Notice in the contracting sarcomere that the thin filaments (blue) have moved toward the middle of the sarcomere. When the muscle is fully contracted, the thin filaments overlap in the middle of the sarcomere. Contraction only shortens the sarcomere; it does not change the lengths of the thick and thin filaments. A muscle can shorten to about one-third of its resting length when all of its sarcomeres are contracted.

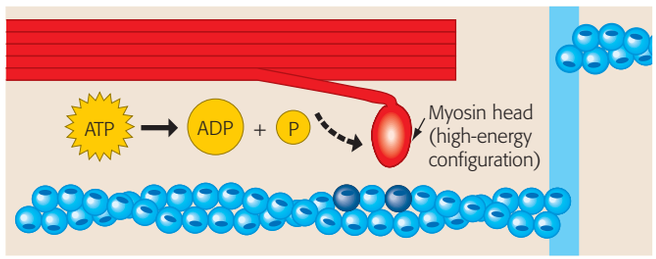
What makes the thin filaments slide? The key event is the binding between parts (called heads) of the myosin molecules in the thick filaments and specific sites on actin molecules in the thin filaments. The process of contraction requires energy, provided by ATP.

Figure 27.33 indicates how sliding is thought to work. 1 ATP binds to a myosin head ( ), causing the head to detach from a binding site on actin ( ). 2 The myosin head gains energy from the breakdown of ATP and changes position. In this high-energy position, the myosin head is cocked like a pistol ready to fire (actually, ready to bind with another site on the actin molecule). 3 The energized myosin head binds to an exposed binding site on actin. 4 The molecular event that actually causes sliding is called the power stroke. The myosin head bends back to its low-energy position, pulling the thin filament toward the center of the sarcomere. 5 After the power stroke, the whole process repeats: More ATP binds, the myosin head attaches to the next binding site along the thin filament and slides it forward, and so on. As long as sufficient ATP is present, the process continues until the muscle is fully contracted or until the signal to contract stops. ☑

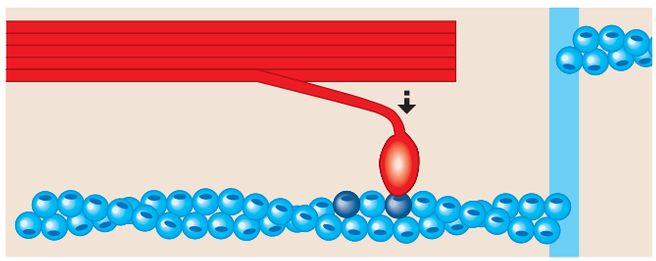
Figure 27.33 The mechanism of filament sliding. Though we show only one myosin head in this figure, a typical thick filament has about 350 heads, each of which can bind and unbind to a thin filament about five times per second.



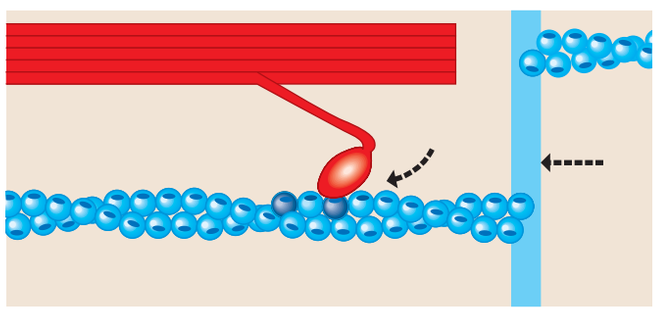
1 ATP binds to a myosin head, which is then released from an actin filament.



2 The breakdown of ATP cocks the myosin head.



3 The myosin head attaches to an actin binding site.



4 The power stroke slides the actin (thin) filament toward the center of the sarcomere.

5 As long as ATP is available, the process can be repeated until the muscle is fully contracted.

☑ CHECKPOINT

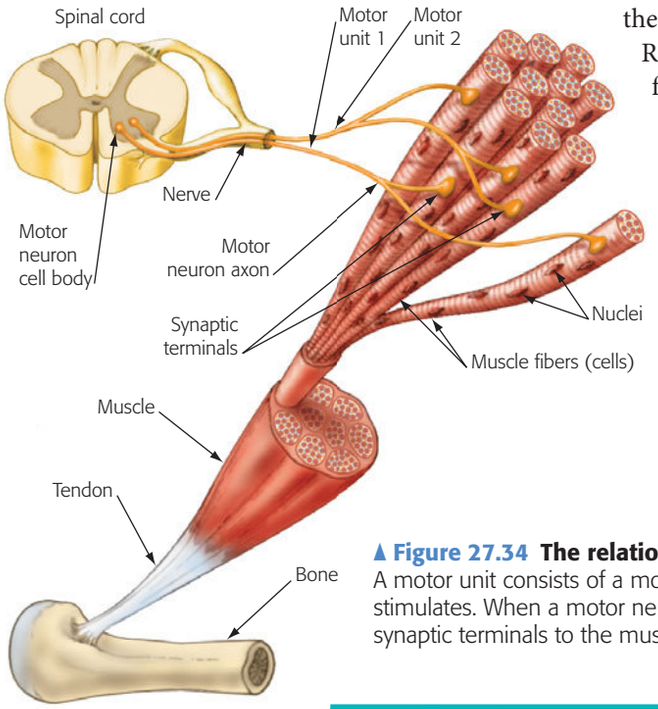
What protein is most abundant in a thin filament of a myofibril? In a thick filament?

Answer: *actin; myosin*

Motor Neurons: Control of Muscle Contraction

The sarcomeres of a muscle fiber do not contract on their own. They must be stimulated to contract by motor neurons, which are part of the central nervous system. Responding to a signal sent from the brain via the spinal cord, a motor neuron releases a neurotransmitter, which causes the muscle fiber to contract. A typical motor neuron can stimulate more than one muscle fiber because each neuron has many branches. In the example shown in **Figure 27.34**, you can see two orange **motor units**, each consisting of a neuron and all the muscle fibers it controls (two or three, in this case).

The organization of individual neurons and muscle cells into motor units is the key to the action of whole muscles. Each motor neuron may serve just one or up to several hundred fibers scattered throughout a muscle. Stimulation of the muscle by a single motor neuron produces only a weak contraction. More forceful contractions result when additional motor units are activated. Thus, depending on how many motor units your brain commands to contract, you can apply a small amount of force to lift a fork or considerably more to lift a barbell. In muscles requiring precise control, such as those controlling eye movements, a motor neuron may control only one fiber. And, as you'll see next, anatomical structures similar to those you have been learning about play an important role in a nonhuman sense.



▲ **Figure 27.34 The relationship between motor neurons and muscle fibers.** A motor unit consists of a motor neuron and the one or more muscle fibers that it stimulates. When a motor neuron receives signals from the CNS, it passes them via synaptic terminals to the muscle fibers, causing the fibers to contract.



Extrahuman Senses THE PROCESS OF SCIENCE

How Do New Senses Arise?

Researchers from the University of Texas investigated the origin of a new sense by starting with **observations** about two species of electric fish, one from Africa and one from South America. These fishes can activate an electric organ, which is actually a modified muscle that has lost its ability to contract and instead uses special ion channel proteins to generate electric fields. Both species use electrical emissions to communicate and to find prey, but the nature of the electrical discharges varies considerably between the two lineages. This led the researchers to **question** whether different ion channel proteins had evolved in the two electric species.

The researchers formed the **hypothesis** that the ion channel genes of the two electric species had mutated in unique ways. In their **experiment**, they determined the DNA sequence of the gene in the two electric fishes and one closely related but nonelectric South American fish. **Figure 27.35** summarizes their **results**. In the common ancestor of all three of these species, a single ion channel gene had duplicated, and the gene copies later mutated into two forms, referred to as *a* and *b*. In the nonelectric fish, both of these genes function in muscles, much as they do in many other vertebrates. In the two species of electric fish, however, gene *a* had mutated into forms that allow the fishes to produce a current in the electric organ. Slight differences in how gene *a* mutated account for the differences in how each species generates electrical signals. Gene *b*, however, functions in the muscles of the electric fishes as it does in nonelectric fishes. This work demonstrates how a new sense can arise from an old one by gene duplication followed by mutation and natural selection.

Location of gene function	African species Electric fish	South American species Electric fish	South American species Nonelectric fish
			
Muscle	Gene *b*	*b*	*a* and *b*
Electric organ	Gene *a* (mutation 1)	*a* (mutation 2)	none

► **Figure 27.35 Duplication of the gene for a muscle ion channel protein led to an electric organ.** In two species of electric fish, the gene for a muscle ion channel protein duplicated and then mutated, producing genes *a* and *b*; gene *a* functions in the electric organ, while gene *b* functions in muscle. In a nonelectric fish species, both genes function in muscle.

Stimulus and Response: Putting It All Together

The forward soars into the air, ready to receive a pass from his teammate and slam it home in an alley-oop **(Figure 27.36)**. Besides enjoying a great play, we can now appreciate these events in terms of sensory input, nervous system integration, and locomotor response.

The forward obtains information about the path of the ball from his sensory structures. Photoreceptors in his eyes track the ball in flight. Sensory neurons convey this information to his brain as a series of action potentials. Within his brain, information about the angle and speed of the ball is integrated. In response, motor neurons signal multiple muscles to perform very specific actions. He jumps upward, twists his body, extends his arms, turns his wrist joints, and flexes his hand muscles. When mechanoreceptors in his hand detect the impact of the ball, this information is communicated and integrated, resulting in signals that move his hand muscles against his finger bones, squeezing his fingers and capturing the ball. His eyes then provide the visual information needed to turn and slam the ball home. The fans see a spectacular play by a talented athlete. But underlying it all is the nervous system directing muscles to respond to information that sensory receptors have gathered about the environment.

We have now completed the unit on animal structure and function. Our overriding theme has been that the evolution of new structures allows adaptations for new functions; that is, the structural adaptations of a cell, tissue, organ, or organ system determine the job it can perform. We'll see the structure-function theme emerge again in the context of adaptations to the environment when we take up the study of plants in the next unit.



► **Figure 27.36 The nervous, sensory, and locomotor systems in action.**



Extrahuman Senses EVOLUTION CONNECTION

Seeing UV

In the Biology and Society section and elsewhere in this chapter, you have read about senses possessed by some animals but not people. Natural selection can foster new adaptations that arise from mutations in genes that control existing adaptations. You have read about one example—which led to the evolution of electroreception in some fishes—in the Process of Science section. This principle is also clearly evident in the evolution of another nonhuman sense: ultraviolet vision.

Many birds can see beyond what we humans can see **(Figure 27.37)**. Ultraviolet (UV) vision—the ability to see light of wavelengths shorter than those in our visual spectrum (see Figure 7.4)—is believed to be important in social communication and food gathering. As you learned in this chapter, visual information is transmitted to the brain after pigment molecules in the eye absorb light. Researchers studying vision in birds found that a single amino acid change in the pigment protein rhodopsin converted it to a UV-detecting form. This is yet another example of a large change—an important extension of a sense—that can be traced to a small change: a single mutation. In nature, if a mutation such as this one confers a survival advantage (the ability to more easily locate food, for example), then natural selection would tend to favor individuals with the mutation. Over time, the new adaptation would eventually become the norm.



◄ **Figure 27.37 A European kestrel: a bird with UV vision.**

Chapter Review

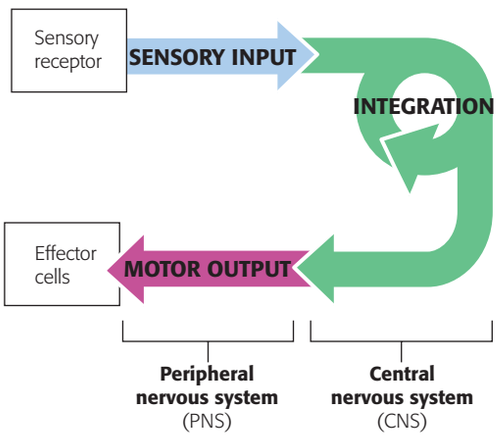
SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

An Overview of Animal Nervous Systems

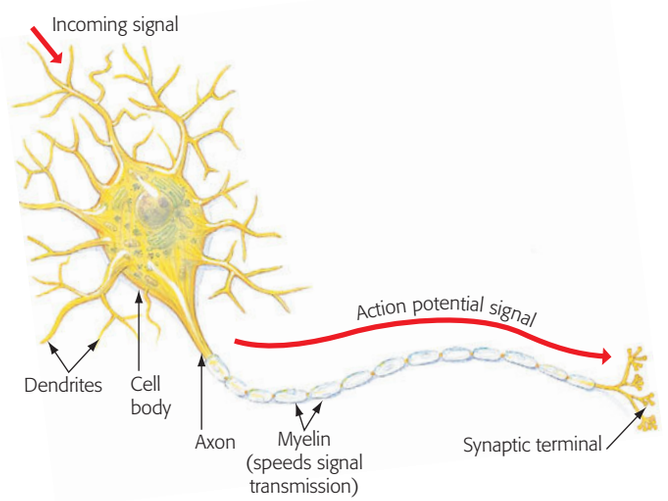
The nervous system is a communication and coordination network composed of neurons, specialized nerve cells capable of carrying signals throughout the body.

Organization of Nervous Systems



Neurons

Neurons are the functional units of the nervous system.



Sending a Signal through a Neuron

At rest, a neuron's plasma membrane has a resting potential caused by the membrane's ability to maintain a positive charge on its outer surface opposing a negative charge on its inner surface. A stimulus alters a portion of the membrane, allowing ions to enter and exit the neuron and creating an action potential. Action potentials are self-propagated in a one-way chain reaction along a neuron. An action potential is an all-or-none event; its size is not affected by differences in stimulus strength. The frequency of action potentials does change with the strength of the stimulus.

Passing a Signal from a Neuron to a Receiving Cell

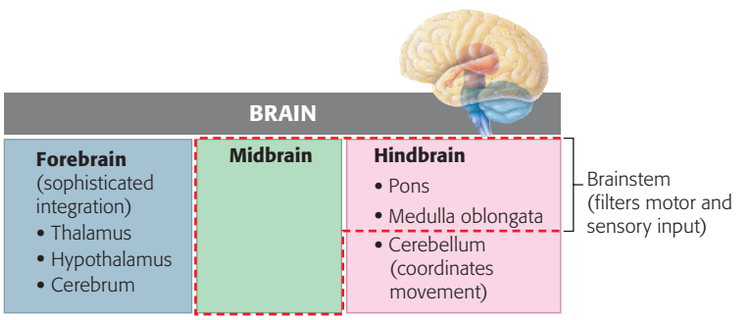
Signals are transmitted beyond an individual neuron at relay points called synapses. In an electrical synapse, electric current passes directly from one neuron to the next. At chemical synapses, the sending cell secretes a chemical signal, a neurotransmitter, which crosses the synaptic cleft (a gap between the cells) and binds to a specific receptor on the surface of the receiving cell. A cell may receive different signals from many neurons. A wide variety of small molecules can act as neurotransmitters. Many drugs act at synapses by increasing or decreasing the normal effect of neurotransmitters.

The Human Nervous System: A Closer Look

The Central Nervous System and the Peripheral Nervous System

NERVOUS SYSTEM			
Central Nervous System (CNS)		**Peripheral Nervous System** (PNS)	
Brain	**Spinal cord:** nerve bundle that communicates with body	**Voluntary nervous system:** voluntary control over muscles	**Autonomic nervous system:** involuntary control over organs • Parasympathetic division: rest and digest • Sympathetic division: fight or flight

The Human Brain



The forebrain's cerebrum, divided into right and left hemispheres, is the largest and most complex part of the brain. In particular, the surface of the cerebrum, the cerebral cortex, is responsible for many of the most distinctive human traits. The right and left cerebral hemispheres specialize in different mental tasks.

The Senses

Sensory Input

The process of sensory transduction:

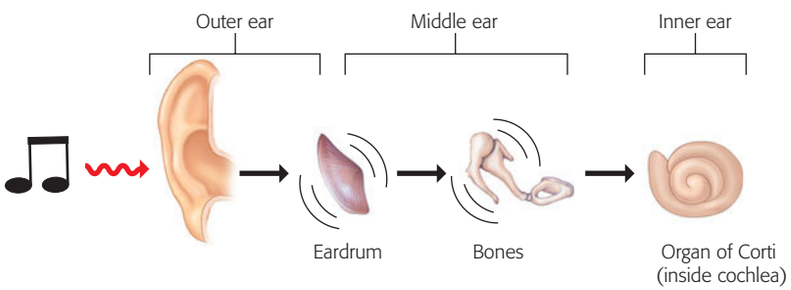


The strength of the stimulus alters the rate of action potential transmission. Some sensory neurons tend to become less sensitive when stimulated repeatedly, a phenomenon known as sensory adaptation. Pain receptors sense stimuli that may indicate tissue damage; thermoreceptors detect heat or cold; mechanoreceptors respond to mechanical energy (such as touch, pressure, or sound); chemoreceptors respond to chemicals in the external environment or body fluids; and electromagnetic receptors respond to electricity, magnetism, or light (photoreceptors).

Vision

In the human eye, the cornea and lens focus light on the retina. The human lens changes shape to bring objects at different distances into sharp focus. The retina contains two types of photoreceptor cells called rods and cones. Rods contain the visual pigment rhodopsin and function in dim light. Cones contain photopsin, which enables us to see color in full light. Nearsightedness, farsightedness, and astigmatism result from focusing problems in the lens. Corrective lenses bend the light rays to compensate.

Hearing



The waves generated in the cochlear fluid move hair cells (mechanoreceptors) of the organ of Corti against an overlying membrane. Bending of the hair cells triggers receptor potentials, sending nerve signals to the brain. Deafness can be caused by infections, injury, or overexposure to loud noises.

Locomotor Systems

Movement is one of the most distinctive features of animals. In the process of locomotor output, the nervous system issues commands to the muscular system, and the muscular system exerts force against the skeleton.

The Skeletal System

The skeletal system functions in support, movement, and the protection of internal organs. The human endoskeleton is composed of cartilage and bone. Movable joints provide flexibility. A bone is a living organ containing several kinds of tissues. It is covered with a connective tissue membrane. Cartilage at the ends of the bone cushions the joints. The human skeleton is versatile, but it is also subject to problems, such as arthritis and osteoporosis. Broken bones can be realigned and immobilized, usually by splints or casts; bone cells then build new bone and repair the break.

The Muscular System

Skeletal muscles pull on bones to produce movements. Antagonistic pairs of muscles produce opposite movements. Each skeletal muscle cell, or fiber, contains bundles of myofibrils, which in striated muscle exhibit alternating light and dark bands. Each myofibril contains bundles of overlapping thick (myosin) and thin (actin) protein filaments. Repeating units of thick and thin filaments, called sarcomeres, are the muscle fiber's contractile units. The sliding-filament model explains the molecular process of muscle contraction. Using ATP, the myosin heads of the thick filaments attach to binding sites on the actin molecules and pull the thin filaments toward the center of the sarcomere. Motor neurons carry action potentials that initiate muscle contraction. A neuron can branch to contact a number of muscle fibers; the neuron and the muscle fibers it controls constitute a motor unit. The strength of a muscle contraction depends on the number of motor units activated.

Stimulus and Response: Putting It All Together

An animal's nervous system connects sensations derived from environmental stimuli to responses carried out by its muscles.

SELF-QUIZ

1. The large, central hub of a neuron, called the _____, contains the nucleus and organelles. Short, numerous fibers called _____ receive incoming messages, while a single long fiber called a(an) _____ conducts signals toward other cells. A neuron ends in many branches, each with a bulb-like _____ that contains neurotransmitters, which can be used to communicate signals to other neurons.
2. What is the function of the myelin sheath?
3. Your nervous system can be divided into two broad subsystems, the _____ and the _____. One of these is made up of nerves that conduct signals to and from the other structures. The other consists of the _____ and _____.
4. The central nervous system is protected by _____, a liquid that cushions it and supplies it with nutrients, and layers of protective tissue called the _____.

5. While driving down the interstate at rush hour, you get cut off by an 18-wheeler and have to slam on the brakes. In addition to a major case of road rage, you also develop a rapid heart rate and a rapid breathing rate. What's causing this increase? Your answer should indicate the branch of the nervous system involved.
6. A victim of a severe head injury can live for years in a nonresponsive state in which the cerebral cortex is not functioning but the person is still alive and performing metabolic functions. Based on your knowledge of brain structure and function, how can this be possible? Make sure your answer indicates which brain structures might be keeping the person alive.
7. How is an action potential different from a receptor potential?
8. For each of the following senses in humans, identify the type of receptor: seeing, tasting, hearing, smelling.
9. Mr. Johnson is becoming slightly deaf. To test his hearing, his doctor holds a vibrating tuning fork tightly against the back of Mr. Johnson's skull. This sends vibrations through the bones of the skull, setting the fluid in the cochlea in motion. Mr. Johnson can hear the tuning fork this way, but not when it is held away from his skull a few inches from his ear. Where is Mr. Johnson's hearing problem located? (Explain your answer.)
   a. in the auditory nerve leading to the brain
   b. in the hair cells in the cochlea
   c. in the bones of the middle ear
   d. in the fluid of the cochlea
10. A human's soft internal organs are protected by the _____ skeleton, while the bones of the limbs make up the _____ skeleton.
11. Arm and leg muscles are arranged in antagonistic pairs. How does this affect their functioning?
    a. It provides a backup if one of the muscles is injured.
    b. One muscle of the pair pushes while the other pulls.
    c. A single neuron controls both of them.
    d. It allows the muscles to produce opposing movements.
12. Muscle A and muscle B are the same size, but muscle A is capable of much finer control than muscle B. Which of the following is likely to be true of muscle A? (Explain your answer.)
    a. It is controlled by more neurons than muscle B.
    b. It contains fewer motor units than muscle B.
    c. It is controlled by fewer neurons than muscle B.
    d. Each of its motor units consists of more cells than the motor units of muscle B.

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

13. Much of what we know about brain function has come from rare individuals whose brains were altered as the result of surgery, accidents, or disease. Suppose a patient has brain surgery on the cerebral cortex, and immediately following the surgery, she appears normal. As she recovers over the next few days, she experiences some unusual things, such as being unable to name objects while looking at them with one eye covered. Her sensory perception seems normal except for when she tries to integrate information. What brain structure might have been damaged during the surgery that would account for these symptoms? Justify your answer.
14. Sensory organs tend to come in pairs. We have two eyes and two ears. Similarly, a planarian worm has two eyecups, a rattlesnake has two infrared receptors, and a butterfly has two antennae. Propose a testable hypothesis that could explain the advantage of having two eyes or ears instead of one.

BIOLOGY AND SOCIETY

15. Brain injuries tend to be so severe because most neurons will not be regenerated once they have been damaged. The use of embryonic stem cells (see Chapter 11) has been proposed as a potential solution to many neurological diseases. Stem cells could be placed into the brain of a person with Alzheimer's or Parkinson's disease. Theoretically, those cells could differentiate into neurons, replacing those that had been killed by the disease. Do you favor or oppose research along these lines? Why? Would your opinion change if the person to be treated with stem cells were a close family member who would die if not treated?
16. Alcohol's depressant effects on the nervous system cloud judgment and slow reflexes. Alcohol consumption is a factor in many fatal traffic accidents in the United States. What are some other impacts of alcohol abuse on society? What are some of the responses of people and society to alcohol abuse? Do you think that alcohol abuse is primarily an individual or societal problem? Do you think our responses to alcohol abuse are appropriate and proportional to the seriousness of the problem?
17. Have you ever felt your ears ringing after listening to music with the volume turned high or attending a loud rock concert? Are you worried that excessively loud music could permanently impair your hearing? Do you think that people are aware of the possible danger of prolonged exposure to loud music? Should anything be done to warn or protect them? If so, what action would you suggest? What effect might warnings have?

Unit 6 Plant Structure and Function

Chapter 28: **The Life of a Flowering Plant**



Chapter Thread: **Agriculture and People**

Chapter 29: **The Working Plant**



Chapter Thread: **The Interdependence of Organisms**



28 The Life of a Flowering Plant



Roasted coffee beans. People have been cultivating, drying, roasting, and drinking coffee for hundreds of years.



CHAPTER CONTENTS

The Structure and Function of a Flowering Plant 606

Plant Growth 613

The Life Cycle of a Flowering Plant 617

CHAPTER THREAD

Agriculture and People

BIOLOGY AND SOCIETY
The Buzz on Coffee Plants 605

THE PROCESS OF SCIENCE
What Happened to the Lost Colony of Roanoke? 616

EVOLUTION CONNECTION
The Problem of the Disappearing Bees 621



Agriculture and People BIOLOGY AND SOCIETY

The Buzz on Coffee Plants

From the dawn of civilization to the frontiers of genetic engineering, human progress has always depended on expanding our use of plants—for food, fuel, clothing, and countless other trappings of modern life. To frame our relationship with plants, think about a particular crop, one that may help get you through a long day of classes: coffee. Today, coffee is one of the most important agricultural products in the world. Americans drink more than $10 billion worth of coffee annually, a startling average of 22 gallons of coffee per American per year.

Ground coffee is made from the seeds of plants belonging to several species in the genus *Coffea*. Historians believe that coffee was discovered in Ethiopia during the 1200s. Locals may have noticed that the plants provided an energizing effect on animals that ate its fruit. African farmers eventually learned to roast, grind, and filter the coffee beans in water. From central Africa, coffee cultivation and consumption spread to the Middle East. By the 1600s, coffee houses had appeared throughout Europe. And by the 1700s, coffee plants imported to the Americas were an important crop. Today, coffee is grown in at least 50 tropical countries around the world. A small but growing percentage of commercial coffee is "Fair Trade Certified." To receive such a designation, farmers agree to provide humane working conditions for their employees and to abide by agricultural practices that promote a healthy and sustainable environment. In exchange, the farmers are guaranteed a fair price for their crop.

Clearly, we have benefited from our agricultural relationship with coffee. But ask yourself this: What is the basis of coffee's popularity? No doubt we love the jolt we get from the caffeine, which is produced in coffee seeds and stimulates the nervous system. It is believed that caffeine acts as a toxin to many herbivores (plant-eaters) and therefore serves as a form of self-defense for the plant. Your morning buzz may therefore be a by-product of an evolutionary adaptation that helps protect the coffee plant from being eaten by pests.

Plants are vital to the well-being of not just humans but the entire biosphere. Above and below the ground, plants provide shelter, food, and breeding areas for animals, fungi, and microorganisms. Because angiosperms—the flowering plants—make up more than 90% of the plant kingdom, we concentrate on them in this unit. (If you'd like to learn about other groups of plants—such as mosses, ferns, and cone-bearing gymnosperms—see Chapter 16.) In this chapter, we begin by examining angiosperm structure, first at the level of the whole plant and then at the microscopic level of tissues and cells. Then we'll see how plant structures function in growth and reproduction.

The Structure and Function of a Flowering Plant


Coffee plant

Angiosperms have dominated the land for more than 100 million years, and about 250,000 species of flowering plants exist today. Most of our foods come from 100 or so species of domesticated flowering plants. Among these foods are roots, such as beets and carrots; the fruits of trees and vines, such as apples, nuts, berries, and squashes; the fruits and seeds of legumes, such as peas, peanuts, and beans; and grains, the fruits of grasses such as wheat, rice, and corn. (Notice that the term *coffee bean* is not strictly correct, because the coffee plant is not a legume; it is coffee seeds that we roast and consume.)

Monocots and Dicots

On the basis of several structural differences, botanists (biologists who study plants) have traditionally classified angiosperms into two groups: monocots and dicots **(Table 28.1)**. The names of the groups refer to embryonic structures called **cotyledons** (also called seed leaves), the first leaves to emerge from a growing seedling. A **monocot** embryo has one seed leaf; a **dicot** embryo has two seed leaves. The largest group of dicots is the **eudicots** (which translates to "true" dicots). In this chapter, we will focus on monocots and eudicots.

Monocots include orchids, palms, and lilies, as well as grains and other grasses. Most monocots have leaves with parallel veins. Monocot stems have vascular tissues (internal tissues that transport water and nutrients) organized into bundles that are arranged in a scattered pattern. The flowers of most monocots have petals and parts in multiples of three. Monocot roots form a fibrous system—a mat of threads—that spreads out just below the soil surface. With most of their roots in the top few centimeters of soil, monocots, especially grasses, make excellent ground covers and can help reduce soil erosion.

Most flowering plants are eudicots, including many food crops (such as nearly all of our fruits and vegetables), the majority of ornamental plants, and most shrubs and trees (except for the gymnosperms). Coffee, for example, grows as a eudicot shrub. Eudicot leaves have a multibranched network of veins, and eudicot stems have vascular bundles arranged in a ring. Eudicot flowers usually have petals and floral parts in multiples of four or five. The large, main root of a eudicot, known as a taproot, goes deep into the soil, as you know if you've ever tried to pull up a dandelion.

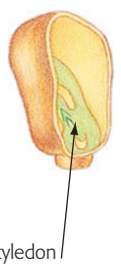
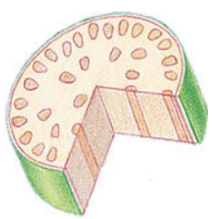
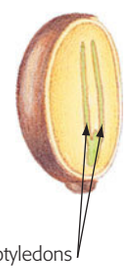
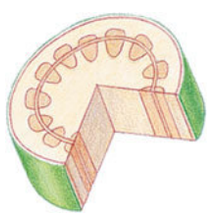
As we saw in the preceding unit on animals, a close look at a structure often reveals its function. Conversely, function provides insight into the "logic" of a structure. In the sections that follow, we'll take a detailed look at the correlation between plant structure and function. ☑

☑ CHECKPOINT

How do the terms *monocot* and *eudicot* relate to an anatomical difference between these two groups of plants?

Answer: *A monocot embryo has a single* (*mono-* means "one") cotyledon (seed leaf), and a eudicot embryo has two (*di-* means "two").

Table 28.1 **Comparing Monocots and Eudicots**

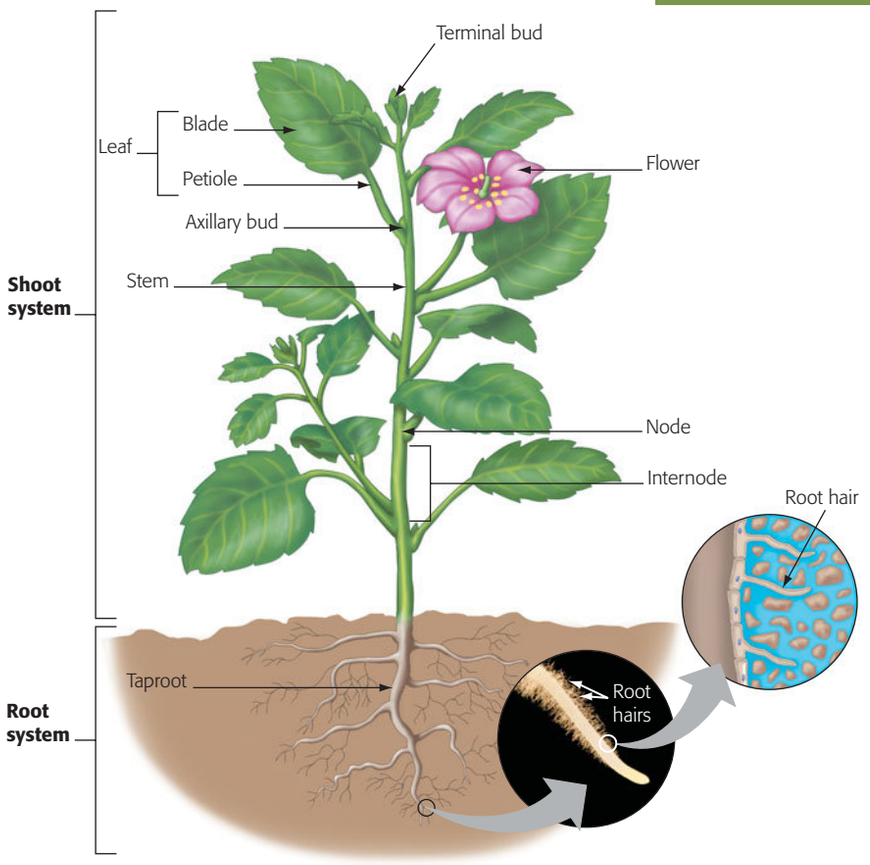
	Seed Leaves	Leaf Veins	Stems	Flowers	Roots
Monocots	 One cotyledon	 Veins usually parallel	 Vascular bundles in scattered arrangement	 Floral parts usually in multiples of three	 Fibrous root system
Eudicots	 Two cotyledons	 Veins usually branched	 Vascular bundles arranged in ring	 Floral parts usually in multiples of four or five	 Taproot usually present

Plant Organs: Roots, Stems, and Leaves

Plants, just like most animals, have organs made up of different tissues, and these tissues in turn are made up of one or more types of cells. An **organ** consists of several types of tissues that together carry out a particular function.

Plants (along with fungi) first occupied land around 475 million years ago (see Chapter 16). Among the evolutionary adaptations that made it possible for plants to thrive on land were structures for absorbing water and minerals from the soil; a large light-collecting surface; the ability to take in carbon dioxide from the air for photosynthesis; and adaptations for surviving dry conditions. In a land plant, the roots (the belowground structures) and the shoots (the aboveground structures, including stems, leaves, and flowers) perform all these vital functions **(Figure 28.1)**. Neither roots nor shoots can survive without the other. Lacking chloroplasts and living in the dark, the roots would starve without sugar and other organic nutrients transported from photosynthetic stems and leaves. Conversely, stems and leaves depend on the water and minerals absorbed by roots.

▼Figure 28.1 The structure of a flowering plant.



Roots

A plant's **roots** anchor it in the soil, absorb and transport minerals and water, and store food. All of a plant's roots make up its **root system**. The fibrous root system of a monocot provides broad exposure to soil water and minerals as well as firm anchorage. In contrast, the eudicot taproot is vertical, with many small secondary roots growing outward. Near the root tips of both monocots and eudicots are tiny projections called **root hairs** that greatly increase the root surface area, providing an extensive outer layer for absorption of water and minerals (Figure 28.1, far right). Each root hair is an outgrowth of a cell on the surface of the root. It is difficult to move an established plant without injuring it because such transplantation often damages the plant's delicate root hairs.

Large taproots, such as those found in carrots, turnips, sugar beets, and sweet potatoes, store food in the form of carbohydrates such as starch **(Figure 28.2a)**. The plants use these stored sugars during periods of active growth and when they are producing flowers and fruit. Other types of modified roots include buttress roots, aerial roots that look like the supporting beams of buildings and support the tall trunks of the trees that produce them **(Figure 28.2b)**.

▼Figure 28.2 Modified roots.



(a) The root of a sugar beet stores carbohydrates.



(b) The buttress roots of this Indonesian Paldoa tree help support the trunk.

Stems

The **shoot system** of a plant is made up of stems, leaves, and structures for reproduction (flowers). As indicated in Figure 28.1, the **stems** generally grow above the ground and support the leaves and flowers. In the case of a tree, the stems are the trunk and all the branches. A stem has **nodes**, the points at which leaves are attached, and **internodes**, the portions of the stem between nodes.

The two types of buds you saw in Figure 28.1 are undeveloped shoots. When a plant stem is growing in length, the **terminal bud**, at the tip of the stem, has developing leaves and a compact series of nodes and internodes. The **axillary buds**, one in each of the crooks formed by a leaf and the stem, are usually dormant. In many plants, the terminal bud produces hormones that inhibit growth of the axillary buds, a phenomenon called **apical dominance**. By concentrating the plant's resources on growing taller, apical dominance is an evolutionary adaptation that increases the plant's exposure to light. Branching is also important for increasing the exposure of the shoot system to the environment, and under certain conditions, the axillary buds begin growing and developing into branches. As any home gardener knows, removing the terminal bud by pruning a fruit tree or "pinching back" a houseplant will make the plant bushier **(Figure 28.3)**.

▼Figure 28.3 Apical dominance and the effect of pruning on a rosemary plant.



The terminal bud of this rosemary plant produces hormones that inhibit growth of the axillary buds, an effect called apical dominance. The result is a tall, thin plant.

This rosemary plant has been pruned, which decreases apical dominance and increases branching and leaf production. The result is an increase in the useful yield of leaves.

Stems can take many forms. Strawberry plants have horizontal stems, or runners, that grow along the ground surface. A runner is a means of asexual reproduction; as shown in **Figure 28.4a**, a new plant can emerge from it. This is why strawberries, if left unchecked, can rapidly fill your garden. If you dig up an iris or ginger plant, you'll see a different stem modification; the large, brownish, rootlike structures near the soil surface are actually horizontal underground stems called **rhizomes (Figure 28.4b)**. Rhizomes store food, and because they have buds, they can also form new plants. About every three years, gardeners can dig up iris rhizomes, split them, and plant the partial rhizomes to get multiple identical plants. A potato plant has rhizomes ending in enlarged structures called **tubers** (the potatoes we eat), where food is stored in the form of starch **(Figure 28.4c)**. The "eyes" of a potato are axillary buds, which can grow into new plants, allowing potatoes to be easily propagated.

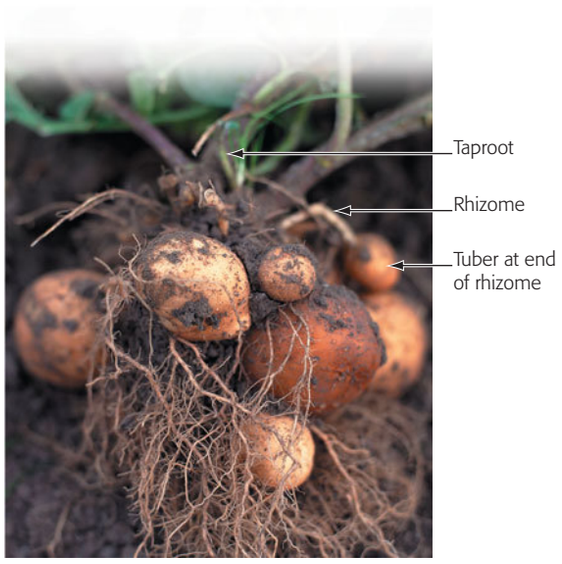
▼Figure 28.4 Modified stems.



(a) Strawberry plants



(b) Ginger plant



(c) Potato plant

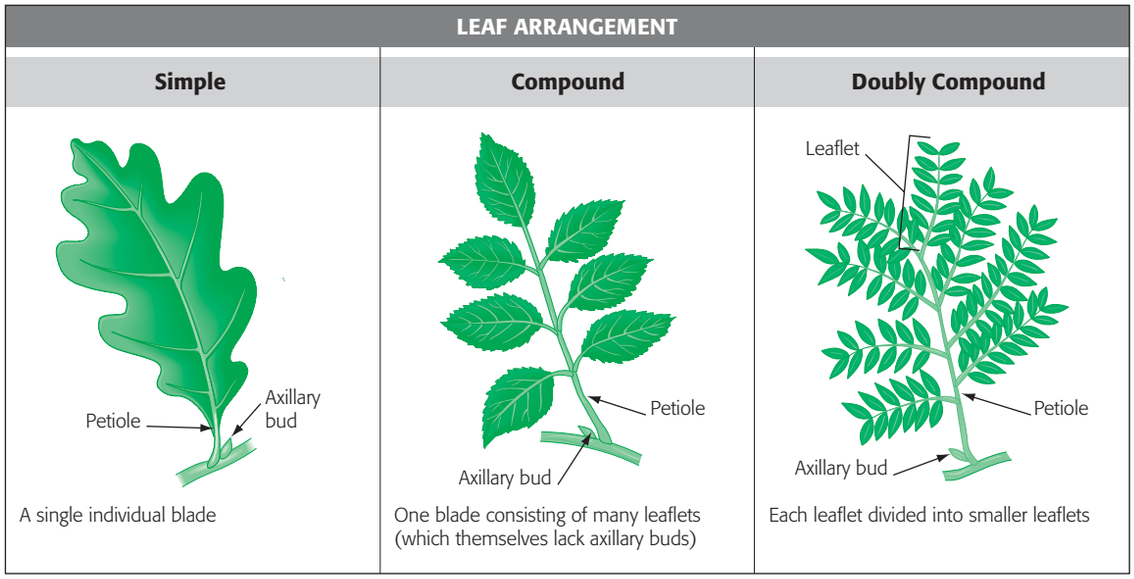
Leaves

Leaves are the primary sites of photosynthesis in most plants, although many plants also have green, photosynthetic stems. A leaf consists of a flattened **blade** and a stalk, or **petiole**, which joins the leaf to the stem (see Figure 28.1).

Plant leaves are highly varied. Leaves can be either simple or compound; some plants even have doubly compound leaves. **Figure 28.5** displays one example of each leaf type, but keep in mind that leaves come in a great variety of sizes and shapes. Grasses and most other monocots have long leaves without petioles. Some eudicots have enormous petioles that contain a lot of water and stored food, such as the edible stalks of celery. A modified leaf called a tendril can help plants such as sweet peas or grapes climb up their supports **(Figure 28.6a)**. And the spines of the cactus **(Figure 28.6b)** are modified leaf parts that may protect the plant from predatory animals. In many cactus species, the main photosynthetic organ is the large green stem, which also stores water.

So far, we have examined plants as we see them with the unaided eye. In the next section, we begin to dissect a plant and explore its microscopic organization. ☑

▼Figure 28.5 Arrangement of leaves. You can distinguish simple leaves from compound leaves by looking for axillary buds: Each leaf has only one axillary bud, where the petiole attaches to the stem; leaflets of compound leaves do not have axillary buds.



▼Figure 28.6 Modified leaves.



(a) Tendrils of a gourd plant



(b) Spines of a cactus

☑ CHECKPOINT

Name the organ you are eating when you eat each of the following foods: celery stalk, lettuce, carrot, potato, turnip.

Answer: *stem, leaf, root, stem, root*

Plant Tissues and Tissue Systems

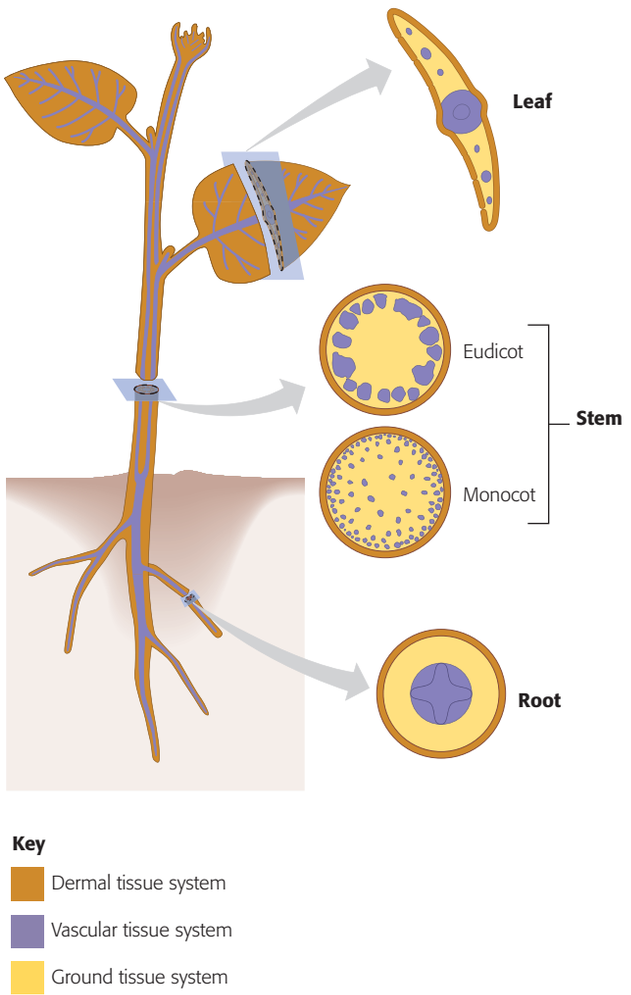
As in animals, the organs of plants contain tissues. Each **tissue** is a group of cells that together perform a specialized function. For example, vascular tissue called **xylem** conveys water and dissolved minerals upward from the roots to the stems and leaves, while **phloem** tissue transports sugars from leaves or storage tissues to other parts of the plant.

A **tissue system** consists of one or more tissues organized into a functional unit within a plant. Each plant organ—root, stem, or leaf—is made up of three tissue systems: the dermal, vascular, and ground tissue systems. Each tissue system is continuous throughout the entire plant body, but the systems are arranged differently in leaves, stems, and roots (Figure 28.7).

The **dermal tissue system** (brown in the figure) forms an outer protective covering. Like our own skin, it forms a first line of defense against physical damage and infectious organisms. On leaves and on most stems, dermal cells secrete a waxy coating called the **cuticle**, which helps prevent water loss. The **vascular tissue system** (purple) provides support and long-distance transport throughout the plant; xylem and phloem are part of this system. The **ground tissue system** (yellow) accounts for most of the bulk of a plant; it has diverse functions, including photosynthesis, storage, and support.

Figure 28.8, a cross section of a eudicot root, illustrates the three tissue systems. The epidermis (the outer layer of the dermal tissue system) is a single layer of tightly packed cells covering the entire root. Water and minerals enter the plant from the soil through these cells. Some of the young epidermal cells grow outward and form root hairs. In the center of the root, the vascular tissue system forms a cylinder, with xylem cells radiating from the center like the spokes of a wheel and phloem cells filling in the wedges between the spokes. The ground tissue system of the root forms the **cortex**, where cells store food and take up water and minerals. The innermost layer of cortex is the **endodermis**, a thin cylinder one cell thick. The endodermis is a selective barrier that regulates the passage of substances between the cortex and the vascular tissue.

All plant stems have vascular tissue systems arranged in numerous vascular bundles. The location and arrangement of these bundles differ between monocots and eudicots (see Figure 28.7). In eudicots, another part of the ground tissue system, known as the **pith**, fills the center of the stem and is often important in food storage.



► **Figure 28.7 The three tissue systems of a plant.** The roots, stems, and leaves of a plant are made from three tissue systems (the dermal tissue system, vascular tissue system, and ground tissue system) that are continuous throughout the plant body.

▼ **Figure 28.8 Tissue systems in a eudicot root.** This colored micrograph is a cross section of a young buttercup root. You can see the single-layered epidermis, the cylindrical vascular tissue system with xylem and phloem, and the ground tissue system that makes up the bulk of the root.

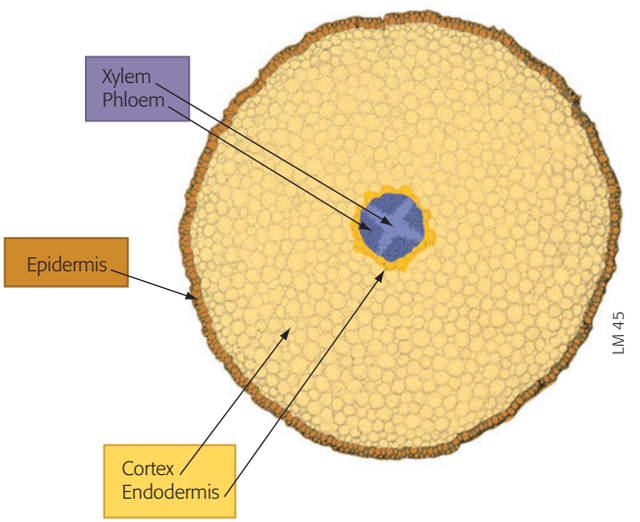
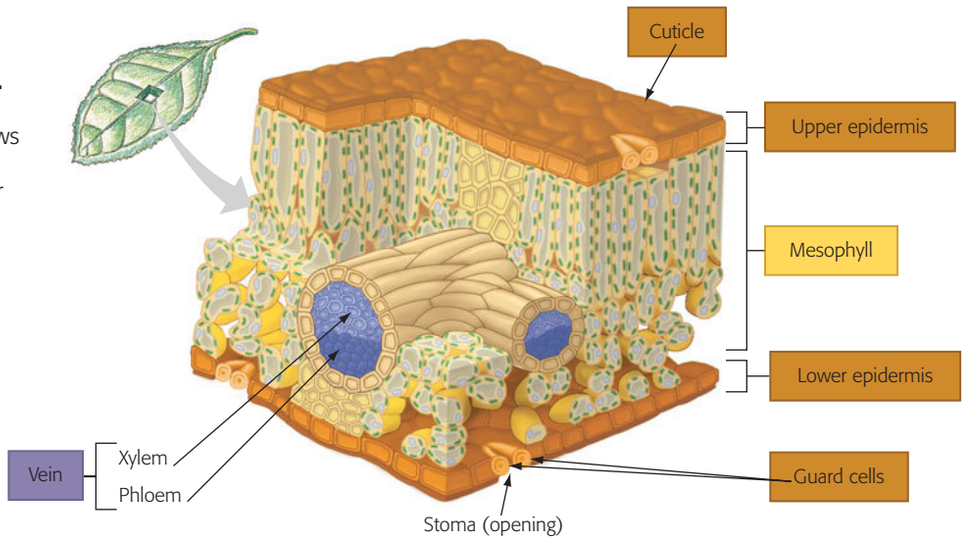


Figure 28.9 illustrates the arrangement of the three tissue systems found in a typical eudicot leaf. The epidermis contains **stomata** (singular, *stoma*), which are tiny pores between two specialized cells called guard cells. The **guard cells** regulate the opening and closing of stomata (see Figure 29.10), allowing gas exchange between the surrounding air and photosynthetic cells inside the leaf.

What structures allow a plant to "breathe"?

The main site of photosynthesis is the **mesophyll**, which is the ground tissue system of a leaf. Mesophyll consists mainly of photosynthetic cells containing chloroplasts (green in Figure 28.9).

The leaf's vascular tissue system is made up of a network of veins. As you can see in Figure 28.9, each vein is a vascular bundle composed of xylem and phloem. The veins are in close contact with the leaf's photosynthetic tissues. This ensures that those tissues are supplied with water and minerals from the soil and that sugars made in the leaves are transported throughout the plant. ✓



► Figure 28.9 Tissue systems in a eudicot leaf. Notice the stoma, a pore on the bottom surface that allows gas exchange between the environment and the interior of the leaf.

✓ CHECKPOINT

Which tissue system is the main site of photosynthesis? Which tissue system covers and protects the outside of the plant?

Answer: ground; dermal

Plant Cells

So far, we have examined plant structure at the level of organs and tissues. Now we'll zoom in even closer to examine cells.

In addition to features shared with other eukaryotic cells (see Figure 4.5), most plant cells have three unique structures, as shown in **Figure 28.10**: **chloroplasts**, the sites of photosynthesis; a large **central vacuole** containing fluid that helps maintain the cell's firmness (also referred to as turgor); and a protective **cell wall** that surrounds the plasma membrane.

Plant cell walls consist largely of the structural carbohydrate cellulose. Some plant cells, especially those that provide structural support, have a two-layered cell wall; a primary cell wall grows first, and then a thicker, more rigid secondary cell wall is deposited between the plasma membrane and the primary wall. Plasmodesmata are open channels in adjacent cell walls through which cytoplasm and various substances can flow from cell to cell.

▼ Figure 28.10 The structure of a plant cell. The colored boxes highlight the unique features of plant cells. The enlargement shows two adjoining cells.

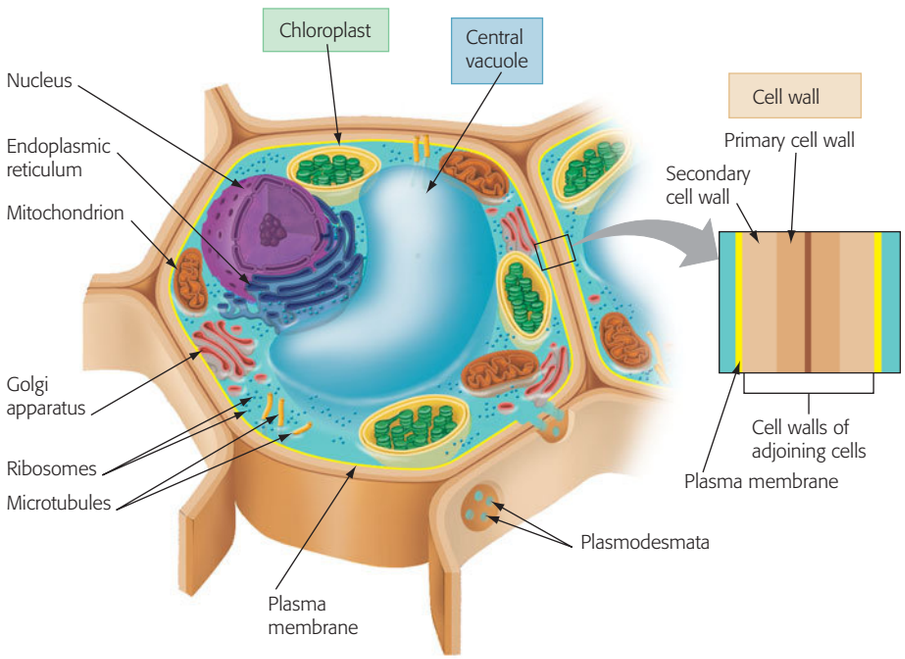


Figure 28.11 presents an overview of plant cell types. **Parenchyma cells** are the most abundant type of cell in most plants. They have only primary (often thin) walls. Parenchyma cells perform a variety of functions, including food storage and photosynthesis. Most parenchyma cells can divide and differentiate (become specialized in their structure and function; see Chapter 11) into other types of plant cells, which they may do during repair of an injury.

Collenchyma cells resemble parenchyma cells in lacking secondary walls, but they have unevenly thickened primary walls. These cells provide support in parts of the plant that are actively growing. Young stems and petioles, for example, often have collenchyma cells just below their surface that elongate with the growing stem (these cells form the "strings" of a celery stalk, for example).

Sclerenchyma cells have thick secondary cell walls (colored pale yellow in Figure 28.11) usually strengthened with **lignin**, the main chemical component of wood. Mature sclerenchyma cells cannot elongate, and they develop only in regions that have stopped growing in length. After they mature, most sclerenchyma cells die, and the rigid cell walls of these dead cells form a "skeleton" that supports the plant much as steel beams do in a building. Sclerenchyma cells make up some commercially important plant products, such as the highly versatile hemp fiber used to make rope and clothing.

Angiosperms have two types of water-conducting cells: tracheids and vessel elements. Both have rigid, lignin-containing secondary cell walls. **Tracheids** are long, thin cells with tapered ends; **vessel elements** are wider, shorter, and less tapered. Water-conducting cells are arranged in chains with overlapping ends that form a system of water-carrying tubes. The tubes are hollow because water-conducting cells are dead when mature; only their cell walls remain. Water passes through pits in the walls of tracheids and vessel elements and through openings in the end walls of vessel elements.

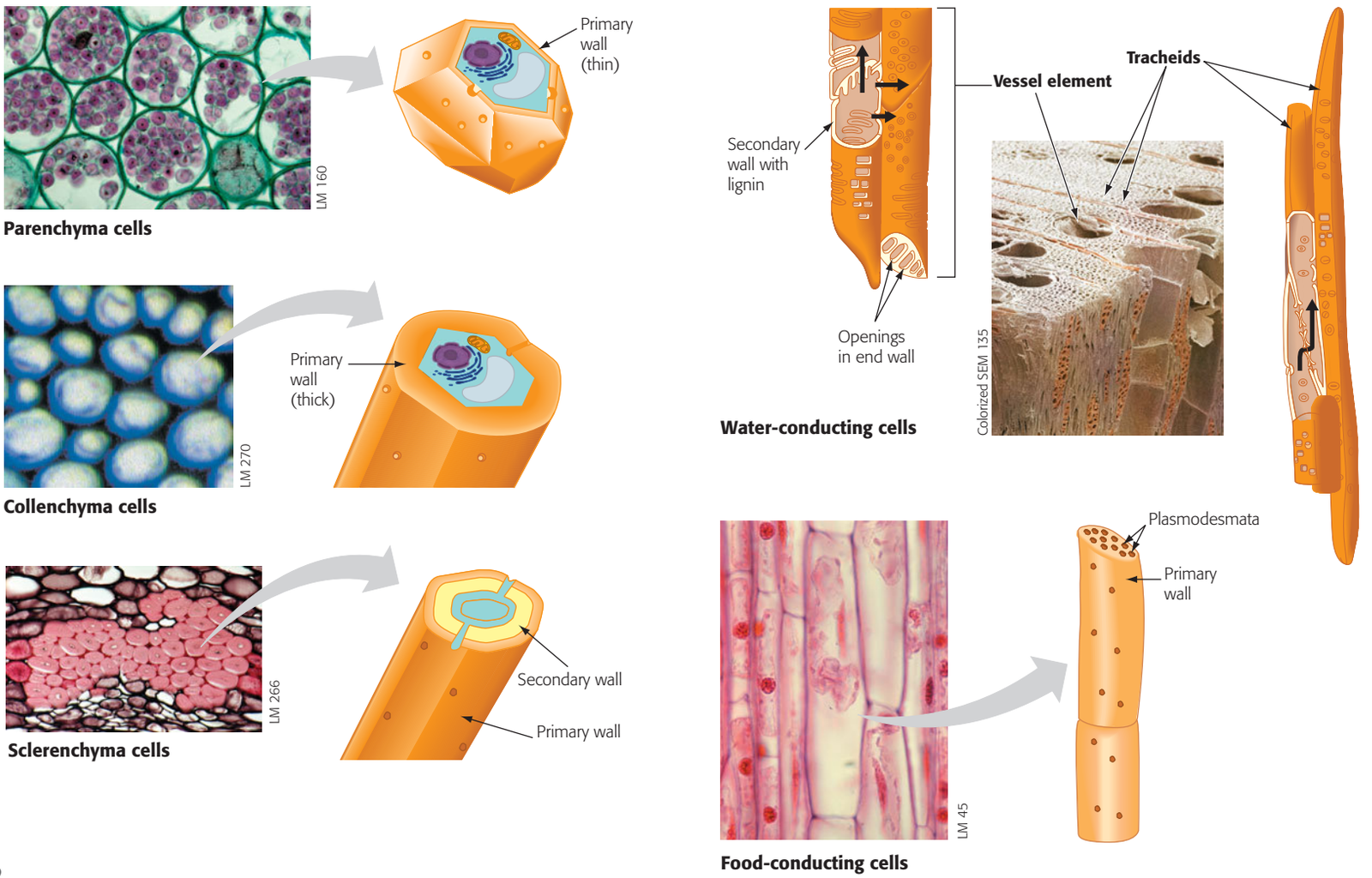
Food-conducting cells are also arranged end to end, forming tubes. Unlike water-conducting cells, however, these cells remain alive at maturity. Their end walls, which are perforated with large plasmodesmata, allow sugars, other compounds, and some minerals to move between adjacent food-conducting cells. ☑

☑ CHECKPOINT

Which of the cell types shown in Figure 28.11 has the potential to give rise to all the others?

Answer: parenchyma

Figure 28.11 Types of plant cells.



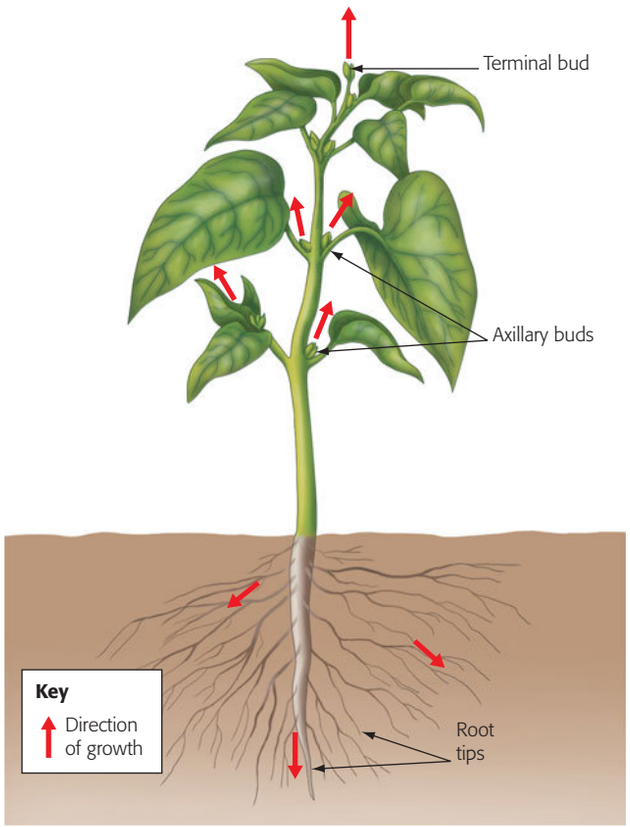
Plant Growth

The growth of a plant differs from that of an animal in a fundamental way. Most animals are characterized by **determinate growth**; that is, they cease growing after reaching a certain size. Most species of plants, in contrast, continue to grow for as long as they live, a condition known as **indeterminate growth**.

Indeterminate growth does not mean that plants are immortal. In fact, different types of plants have very different life spans (Figure 28.12). Plants called **annuals** emerge from seed, mature, reproduce, and die in a single year or growing season. Our most important food crops—wheat, corn, and rice, for example—are annuals. **Biennials** live for two years; flowering and seed production usually occur during the second year. Carrots are biennials, but we usually harvest them in their first year and so miss seeing their flowers. Plants that live and reproduce for many years, including trees, shrubs (such as the coffee plant), and some grasses, are known as **perennials**. Some perennials have life spans well beyond the longest-lived animals; for example, some bristlecone pines have been alive for more than 4,500 years.

Primary Growth: Lengthening

Growth in all plants is made possible by tissues called meristems. A **meristem** consists of undifferentiated (unspecialized) cells that divide when conditions permit, generating new cells and tissues. Meristems at the tips of roots and in the buds of shoots are **apical meristems**. Cell division in apical meristems produces new cells that enable a plant to grow in length, a process called **primary growth** (Figure 28.13). Tissues produced by primary growth are called primary tissues.



◀ **Figure 28.13 Primary growth at apical meristems.** Meristems are tissues responsible for growth in all plants. The apical meristems are located at the root tips and in the buds of shoots.

▼ **Figure 28.12 Plants with varying life spans.**

PLANT LIFE SPANS

Annuals (live for just one growing season)	**Biennials** (live for two growing seasons)	**Perennials** (live for many growing seasons)
		
Rice	Wild chervil (also called cow parsley)	Coffee plants

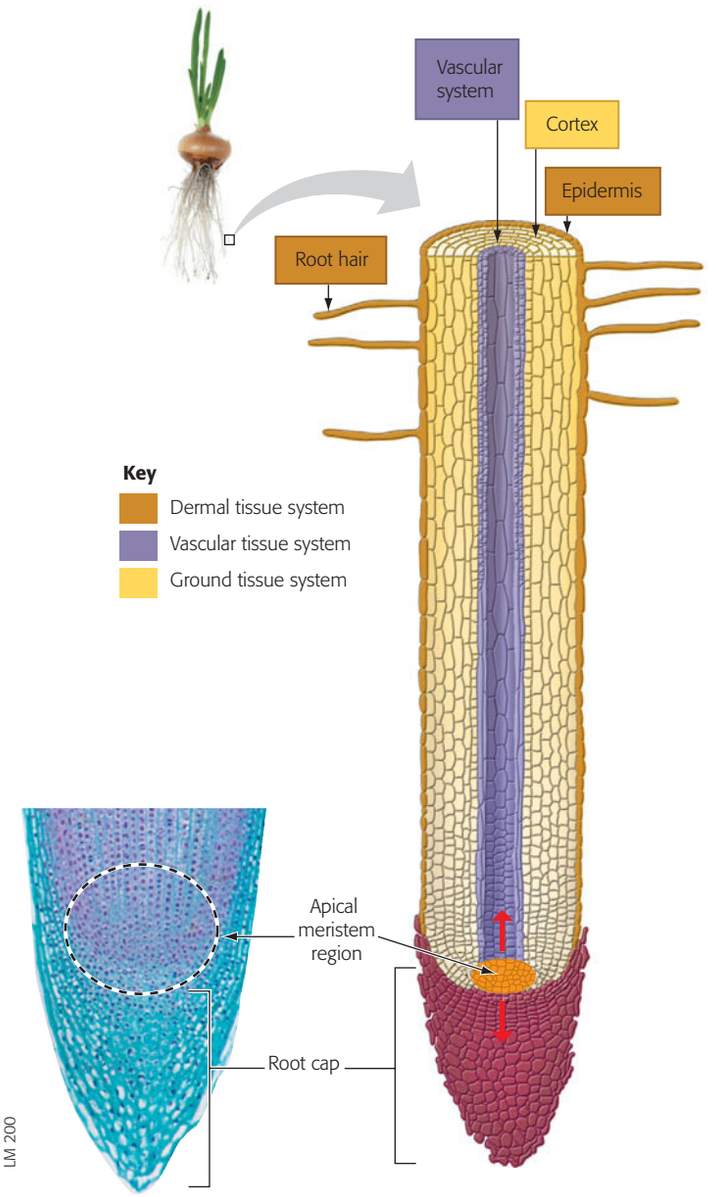
☑ CHECKPOINT

What two basic cellular mechanisms account for primary growth?

Answer: cell division and cell lengthening

Figure 28.14 shows a slice through a growing onion root. Primary growth enables roots to push through the soil. (A very similar process results in the upward growth of shoots.) At the tip of the root is the **root cap**, a thimble-like cone of cells that protects the delicate, actively dividing cells of the apical meristem. The root's apical meristem (marked with the orange oval in the art and circled in the micrograph) replaces cells of the root cap that are scraped away by the soil (downward arrow) and produces cells for primary growth (upward arrow). Primary growth is achieved not only by cell division but also by the lengthening of cells just above the apical meristem (see Figure 28.14, center).

▼Figure 28.14 Close-up of primary growth in a root tip. Primary growth is achieved through two mechanisms. Cells within the apical meristem actively divide. In addition, cells behind the apical meristem elongate up to tenfold.



These cells can undergo a tenfold increase in length, mainly by taking up water. Elongation of these cells is what actually forces a root down through the soil. The elongating cells begin to differentiate, forming primary tissues that develop into the epidermis, cortex, and vascular tissue (see Figure 28.14, top). Cells of this last type eventually differentiate into vascular tissues called primary xylem and primary phloem. ☑

Secondary Growth: Thickening

In addition to lengthwise primary growth, the stems and roots of many plant species also thicken by a process called **secondary growth (Figure 28.15)**. Such thickening is most evident in the woody plants—trees, shrubs, and vines—whose stems last from year to year and consist mainly of thick layers of mature, mostly dead xylem tissue, called **wood**. Tissues produced by secondary growth are called secondary tissues.

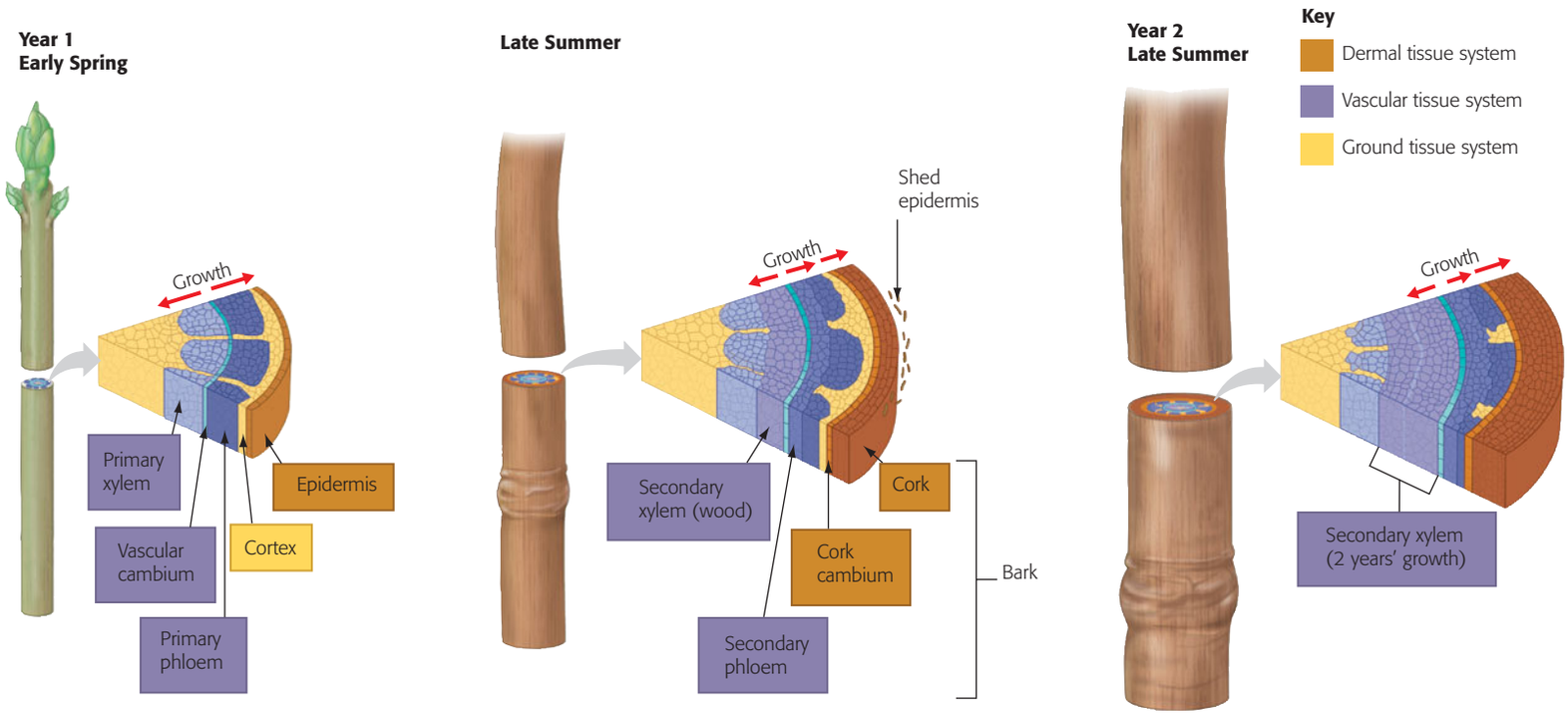
Secondary growth involves cell division in two meristems we have not yet discussed: the vascular cambium and the cork cambium. The **vascular cambium** (blue-green in **Figure 28.16**) is a cylinder of actively dividing cells between the primary xylem and primary phloem, as you can see in the pie-shaped section at the left of the figure. Secondary growth (red arrows) adds cells on either side of the vascular cambium.

The middle and right drawings in Figure 28.16 show the results of secondary growth. In the middle drawing, the vascular cambium has given rise to two new tissues: secondary phloem to its exterior and secondary xylem to its interior. Yearly production of a new layer of secondary xylem accounts for most of the growth in thickness of a perennial plant.

▼Figure 28.15 Secondary growth. Trees (such as these live oaks) thicken from year to year due to secondary growth.

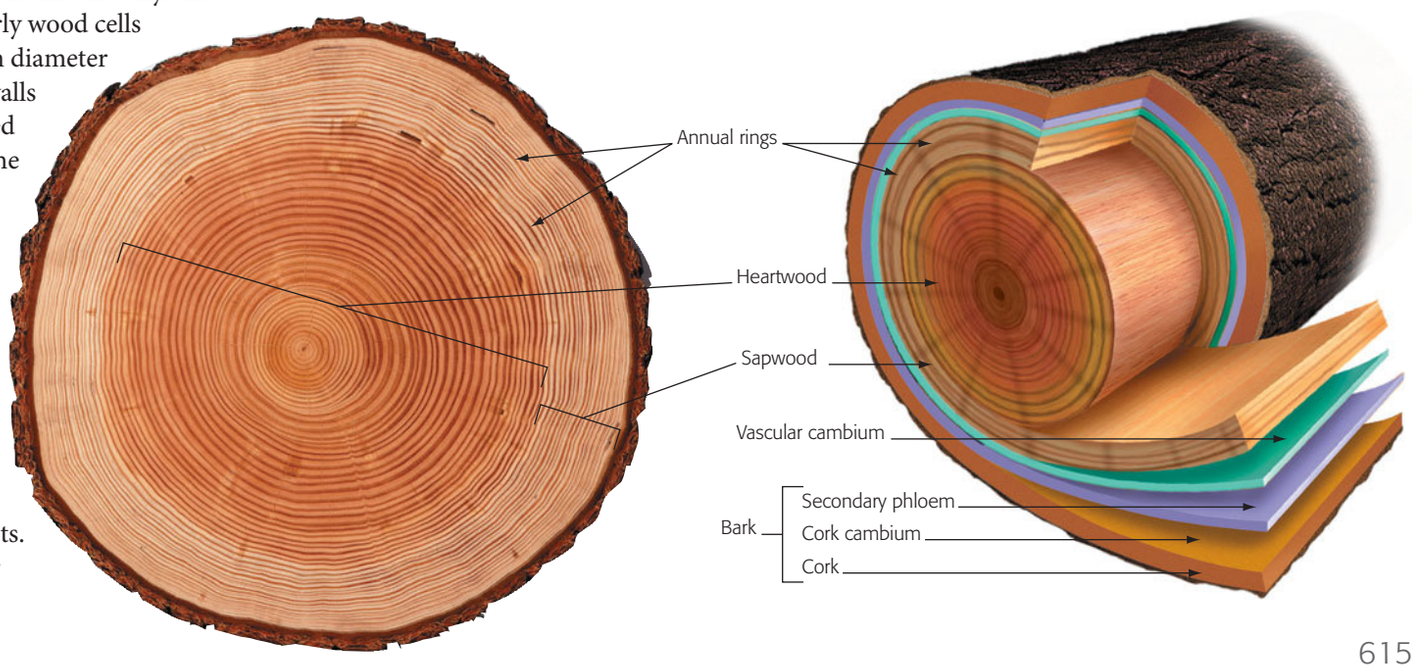


Figure 28.16 Secondary growth of a woody stem. The branches of most woody plants are made up of tissues of varying ages, with the youngest regions near the tip and the older regions nearer the trunk. The cross section at the left shows a region of the stem that is just beginning secondary growth. The middle and right cross sections show progressively older regions.



Annual growth rings result from the layering of secondary xylem **(Figure 28.17)**. The layers are visible as rings because of uneven activity of the vascular cambium during the year. In woody plants that live in temperate regions, such as most of the United States, the vascular cambium becomes dormant each year during winter, and secondary growth is interrupted. When secondary growth resumes in the spring, a cylinder of early wood forms. Made up of the first new xylem cells to develop, early wood cells are usually larger in diameter and have thinner walls than those produced later in summer. The boundary between the large cells of early wood and the smaller cells of the late wood produced during the previous growing season is usually a distinct ring visible in cross sections of tree trunks and roots. As you've probably heard, a tree's age can be estimated by counting its annual rings. The rings may have varying thicknesses, reflecting the amount of seasonal growth in different years and therefore climate conditions. In fact, the pattern of growth rings in older trees is one source of evidence for recent global climate change. As we'll see in the Process of Science section, tree ring data can even provide insight into subjects outside the bounds of science.

Figure 28.17 Anatomy of a tree trunk. On the left, you see a cross section of a locust trunk, with several decades of growth rings visible. On the right, the various layers of a mature trunk are separated for easier viewing.



The epidermis and cortex make up the young stem's external covering (see Figure 28.16). When secondary growth begins, the epidermis is shed and is replaced with a new outer layer called **cork**. After they mature, cork cells die, leaving behind thick, waxy walls that protect the underlying tissues of the stem. Cork is produced by a meristem tissue called the **cork cambium**. Everything external to the vascular cambium (the secondary phloem, cork cambium, and cork) is called **bark**.

The bulk of a tree trunk is dead tissue. The heartwood, in the center of the trunk, consists of older layers of secondary xylem. These cells no longer transport water; they are clogged with resins and other compounds that make the heartwood very dense and resistant to rotting. The lighter-colored sapwood consists of younger secondary xylem that does conduct water.

Why are baseball bats usually made from heartwood?

Thousands of useful products are made from wood—from construction lumber to fine furniture, musical instruments, paper, and many chemicals, such as artificial vanilla flavoring. Among the qualities that make wood so useful are a unique combination of strength, hardness, lightness, durability, and workability. In many cases, there is simply no good substitute for wood. A wooden oboe, for instance, produces far richer sounds than a plastic one, and fence posts made of heartwood often last much longer in the ground than metal ones. ☑

☑ CHECKPOINT

What type of plant tissue makes up wood? What is bark?

Answer: secondary xylem; all tissues exterior to the vascular cambium: secondary phloem, cork cambium, and cork

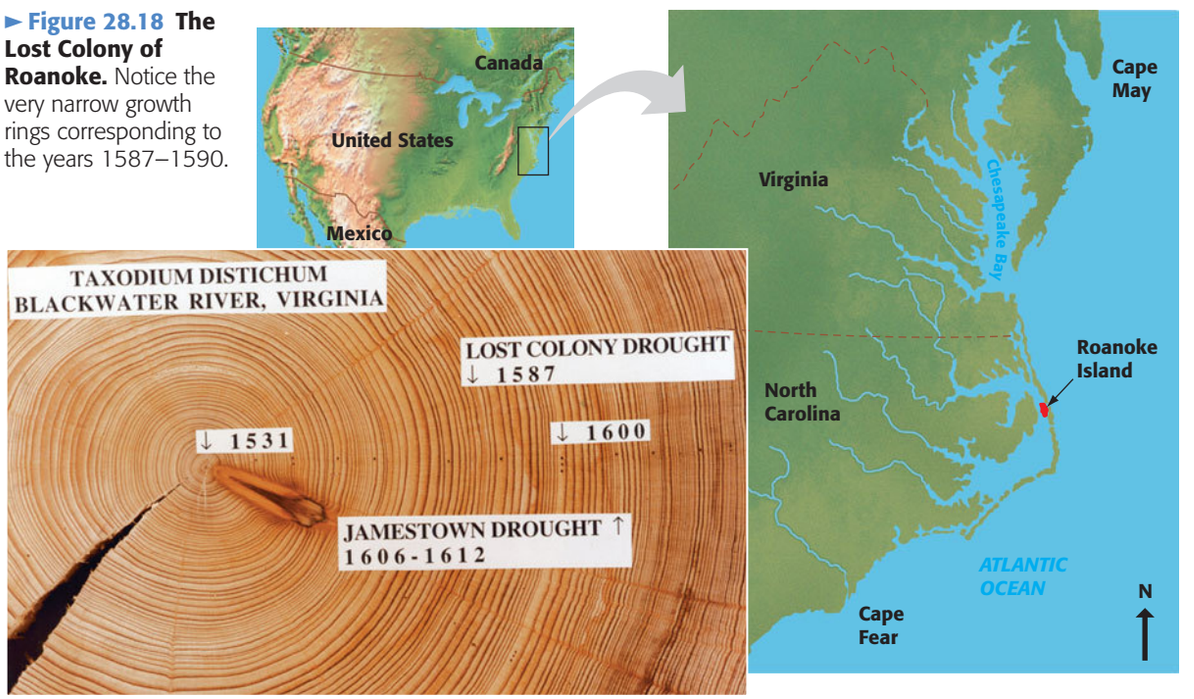


Agriculture and People THE PROCESS OF SCIENCE

What Happened to the Lost Colony of Roanoke?

The ability of people to settle new lands successfully often depends on their ability to maintain a healthy system of agriculture. On July 22, 1587, a group of 121 English settlers landed on Roanoke Island, in present-day North Carolina **(Figure 28.18)**. Their supply ship returned to England later that year, leaving 115 colonists behind. When the next ship returned three years later, the settlement was deserted. There were no signs of struggle, yet no trace of the colonists could be found, and all the buildings had been dismantled. The cause of the disappearance of the "Lost Colony" of Roanoke has long intrigued historians.

In 1998, a group of biologists made the **observation** that a large number of very old bald cypress trees (*Taxodinum distichum*) around Roanoke Island could provide a reliable record of the climate over the past 800 years. This led them to **question** whether the tree ring data could provide insight into the colony's mysterious disappearance. Their **hypothesis** was that the loss of the colony corresponded to a period of drought, leading to the **prediction** that the tree ring data would show abnormal growth during the years after settlement. Their **experiment** involved analyzing dozens of trees that covered the period 1185–1984. Their **results** showed that the colonists had the bad luck to arrive at the start of the worst three-year drought in the southeastern United States in 800 years. Indeed, the year they settled was the driest year on record. These data indicate that it is not necessary to invoke a conflict to explain the disappearance of the Lost Colony; the drought and the resulting inability of the colonists to cultivate plants could have forced them to abandon the settlement.



► **Figure 28.18 The Lost Colony of Roanoke.** Notice the very narrow growth rings corresponding to the years 1587–1590.

The Life Cycle of a Flowering Plant

The life cycle of an organism is the sequence of stages from the adults of one generation to the adults of the next. In completing the life cycle, many flowering plants can reproduce both asexually and sexually, and both modes have played an important role in the evolutionary adaptation of plant populations to their environments. Figure 28.19 shows three examples of **asexual reproduction**, the creation of offspring derived from a single parent without fertilization. Through asexual reproduction, a single plant can produce many offspring quickly and efficiently. This ability of plants is useful in agriculture because it allows farmers to grow a large crop of identical plants from a parent with desirable traits. For example, because navel oranges lack seeds, they can only be propagated asexually; every navel orange tree growing today is a clone of a single tree discovered in Brazil around 1820. As in animals, **sexual reproduction** in plants involves **fertilization**, the union of gametes from two parents to produce genetically distinct offspring. This section discusses the sexual life cycle of flowering plants, starting with a look at the flower.

▼ **Figure 28.19 Asexual reproduction in plants.**



Garlic. This garlic bulb is actually an underground stem that functions in storage. A single large bulb fragments into several cloves. Each clove can give rise to a separate plant.



Holly trees. Each of the small trees is a sprout from the roots of a single holly tree. Eventually, one or more of these root sprouts may take the place of its parent.

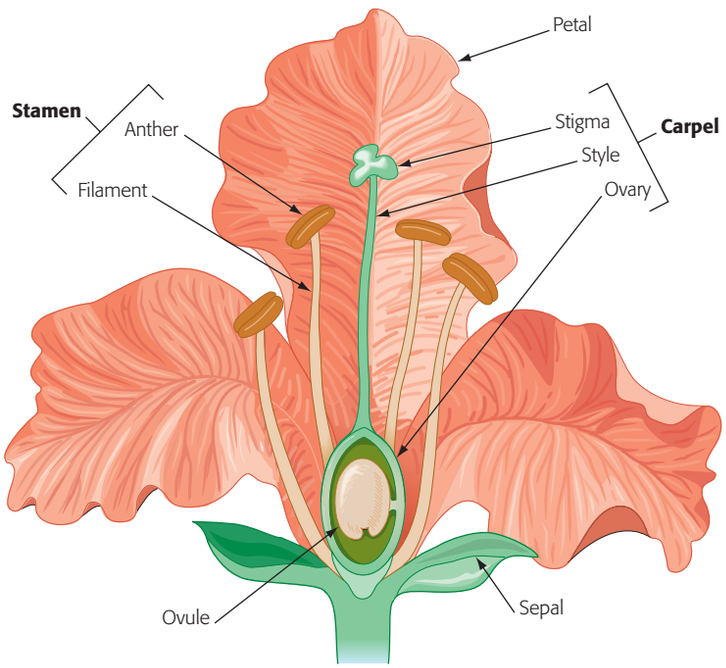


Creosote bushes. This ring of plants is a clone of creosote bushes growing in the Mojave Desert in southern California. All these bushes came from generations of asexual reproduction by roots. This clone apparently began with a single plant that germinated from a seed about 12,000 years ago. The original plant probably occupied the center of the ring.

The Flower

In angiosperms, the structure specific to sexual reproduction is the **flower**. The main parts of a flower—the sepals, petals, stamens, and carpels—are modified leaves (Figure 28.20; also see Figure 28.1). The **sepals** enclose and protect the flower bud. The **petals** are often colorful and fragrant, which may serve to advertise the flower to insects and other pollinators.

The flower's reproductive organs are the stamens and carpel. A **stamen** consists of a stalk (filament) tipped by an **anther**. Within the anther are sacs where meiosis occurs and pollen grains develop. Pollen grains house the cells that develop into sperm. A **carpel** has a long slender neck (the style) with a sticky stigma at its tip. The **stigma** is the landing platform for pollen grains. The base of the carpel is the **ovary**. Within the ovary are reproductive structures called **ovules**, each containing one developing egg and the cells that support it. The term pistil is sometimes used to refer to a single carpel or a group of fused carpels. ☑



◄ **Figure 28.20 The structure of a flower.** The flower is the structure used by angiosperms for sexual reproduction.

☑ CHECKPOINT

Pollen develops within the _____ of sperm-producing organs called stamens. Ovules develop within the ovaries of egg-producing organs called _____.

Answer: *anthers; carpels*

Overview of the Flowering Plant Life Cycle

The life cycle of a sexually reproducing angiosperm is shown in **Figure 28.21**. After fertilization, the ovule of a flower matures into a seed containing the embryo.

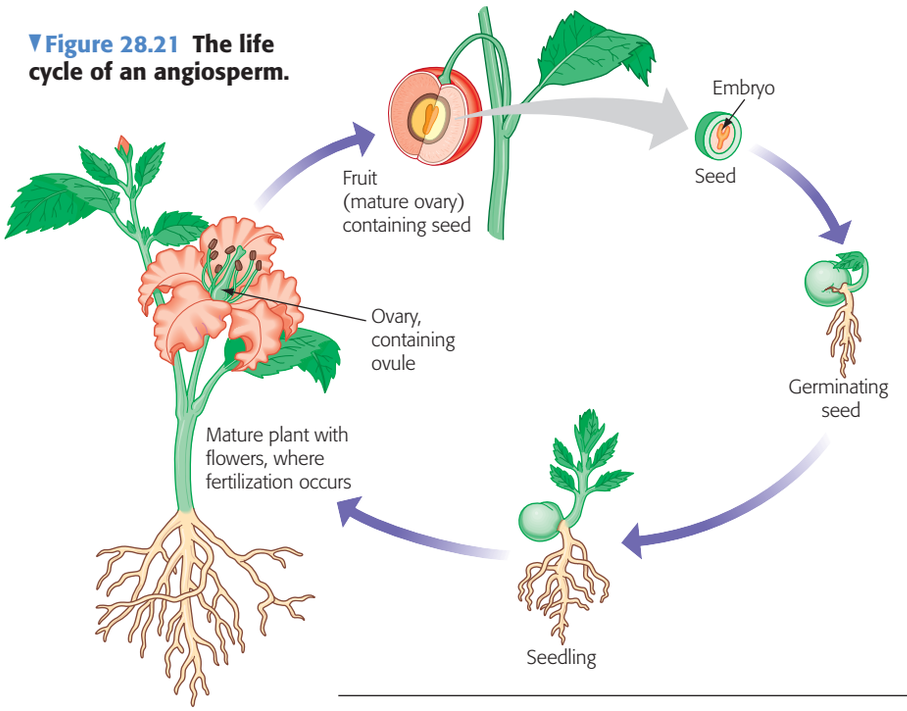


Figure 28.21 The life cycle of an angiosperm.

Meanwhile, the ovary develops into a fruit, which protects the seed and aids in dispersing it. Completing the life cycle, the seed **germinates** (begins to grow), the embryo develops into a seedling, and the seedling grows into a mature plant.

Let's look a bit closer at this process from a genetic point of view. The life cycles of all plants include a haploid generation (when each cell has a single set of chromosomes, abbreviated *n*) and a diploid generation (having two sets of chromosomes, abbreviated 2*n*; see Figure 16.10). The roots, stems, leaves, and most of the reproductive structures of angiosperms are diploid. The diploid plant body, called a **sporophyte**, produces the anthers and ovules in which cells undergo meiosis to produce haploid cells called spores. Each spore then divides via mitosis and becomes a multicellular **gametophyte**, the plant's haploid generation. The gametophyte produces gametes by mitosis. Fertilization occurs when the male and female gametes (sperm and egg, respectively) unite, producing a diploid zygote. The life cycle is completed when the zygote divides by mitosis and develops into a new sporophyte. In the rest of this section, we'll examine each stage in the angiosperm sexual life cycle in more detail.

Pollination and Fertilization

Fertilization requires gametes, which are produced by gametophytes. The male gametophyte is the **pollen grain**, which is essential for pollination and produces sperm. The female gametophyte is a multicellular structure called the **embryo sac**, which produces the egg. As shown at the top of **Figure 28.22**, 1 cells within a flower's anthers 2 undergo meiosis to form four haploid spores. 3 Each spore then divides by mitosis into two haploid cells. A thick wall forms around these cells, and the resulting pollen grain is ready for release from the anther.

Moving to the bottom of the figure, we see that 1 within an ovule, a central cell enlarges and 2 undergoes meiosis, producing four haploid spores. Three of the spores usually degenerate, but the surviving one enlarges and 3 divides by mitosis, producing the embryo sac. The sac contains a large central cell with two haploid nuclei. One of its other cells is the haploid egg, ready to be fertilized.

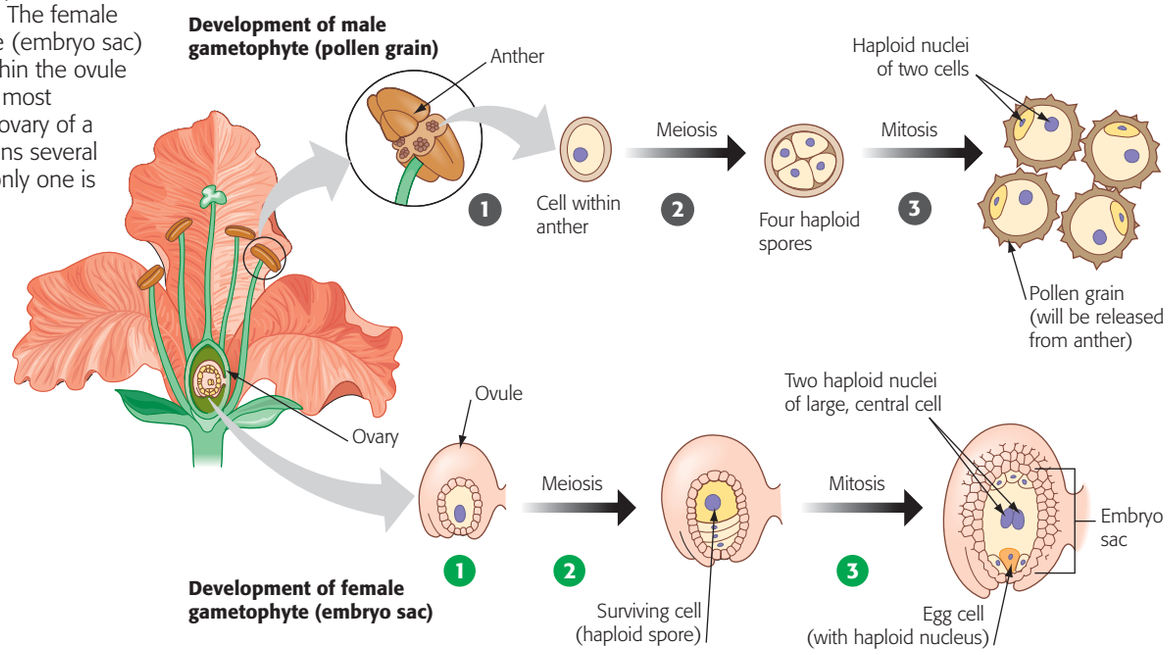
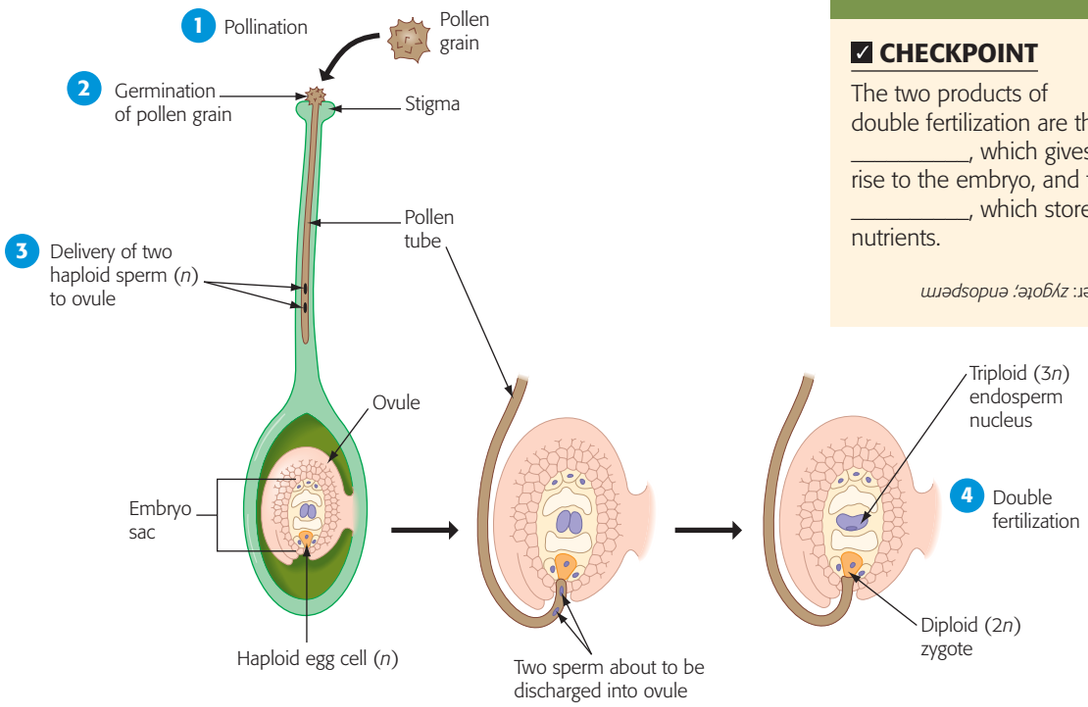


Figure 28.22 Development of gametophytes in an angiosperm. The male gametophyte (pollen grain) develops within the anther (top). The female gametophyte (embryo sac) develops within the ovule (bottom). In most species, the ovary of a flower contains several ovules, but only one is shown here.

How does fertilization occur? As shown in **Figure 28.23**, the first step is **1 pollination**, the delivery of pollen grains from anther to stigma. Many angiosperms are dependent on insects, birds, or other animals to transfer their pollen (a fact we will discuss further in the Evolution Connection section). But the pollen of some plants, such as grasses, is wind-borne—as anyone with pollen allergies knows! **2** After pollination, the pollen grain germinates on the stigma. It divides by mitosis, forming **3** two haploid sperm that travel to the ovule through a pollen tube. **4** One sperm fertilizes the egg, forming the diploid zygote. The other sperm contributes its haploid nucleus to the large diploid central cell of the embryo sac. This cell, now with a triploid ($3n$) nucleus, will give rise to a food-storing tissue called **endosperm**. The formation of both a zygote and a fertilized central cell with a triploid nucleus is called **double fertilization**. This occurs only in plants, mainly in angiosperms. ☑

▼Figure 28.23 Pollination and double fertilization.



☑ CHECKPOINT

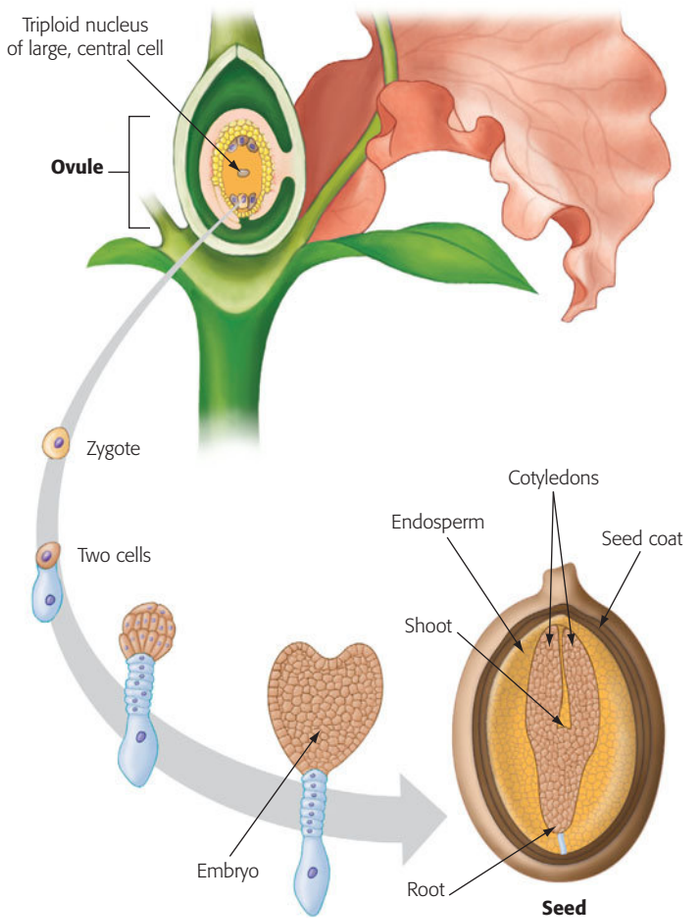
The two products of double fertilization are the _____, which gives rise to the embryo, and the _____, which stores nutrients.

Answer: zygote; endosperm

Seed Formation

After fertilization, the ovule, containing the zygote and the triploid central cell, begins developing into a seed **(Figure 28.24)**. The zygote divides via mitosis into a ball of cells that becomes the embryo. Meanwhile, the triploid cell divides and develops into the endosperm. As cotyledons develop, they absorb nutrients from the endosperm. The result of embryonic development in the ovule is a mature seed (see Figure 28.24, bottom). A **seed** is a plant embryo and endosperm packaged within a tough protective covering called a **seed coat**. (When you grind coffee, you can't see the embryo contained within the coffee bean—which is actually a seed—because it was destroyed by the drying and roasting process.)

At this point, the embryo stops developing and the seed becomes dormant; growth and development are suspended until the seed germinates. Seed dormancy is an important evolutionary adaptation. It allows time for seed dispersal and increases the chance that a new generation of plants will begin growing only when environmental conditions, such as temperature and moisture, favor survival. ☑



◄Figure 28.24 Development of a seed. The plant in this drawing is a eudicot; a monocot would have only one cotyledon.

☑ CHECKPOINT

Of these human structures—sperm, egg, ovary, embryo—which one is analogous to a plant seed?

Answer: embryo (a seed contains a plant embryo suspended during growth)

Fruit Formation

Have you eaten a plant ovary today?

Fruit, among the most distinctive features of angiosperms, develop at the same time seeds do. A **fruit** is a mature ovary that acts as a vessel, housing and protecting seeds and helping disperse them from the parent plant. A corn kernel is a fruit, as is a peach, tomato, or pea pod.

The photographs in **Figure 28.25** illustrate the changes in a pea plant that lead to pod formation. (1) Soon after pollination, (2) the flower drops its petals and the ovary starts growing. The ovary expands tremendously, and its wall thickens, (3) forming the pod, or fruit, which holds the seeds. Peas are usually harvested at this stage. If the pods are allowed to develop further, they become dry and brownish and will split open, releasing the dried seeds.

Mature fruits can be either fleshy or dry **(Figure 28.26)**. Oranges, apricots, and grapes are examples of fleshy fruits, in which the wall of the ovary becomes soft during ripening. Dry fruits include beans, nuts, and grains. The dry, wind-dispersed fruits of cereal grains—such as wheat, rice, and barley—are harvested while on the plant and serve as major staple foods for people. Edible fruits are usually nutritious, sweet tasting, and vividly colored, advertising their ripeness. When an animal eats the fruit, it digests the fruit's fleshy part, but the tough seeds usually pass through the animal's digestive tract and are left behind unharmed, complete with a handy supply of fertilizer.



▲ **Figure 28.25** **Development of a pea pod (fruit).**

▼ **Figure 28.26** **A variety of fruits.**



Fleshy fruits



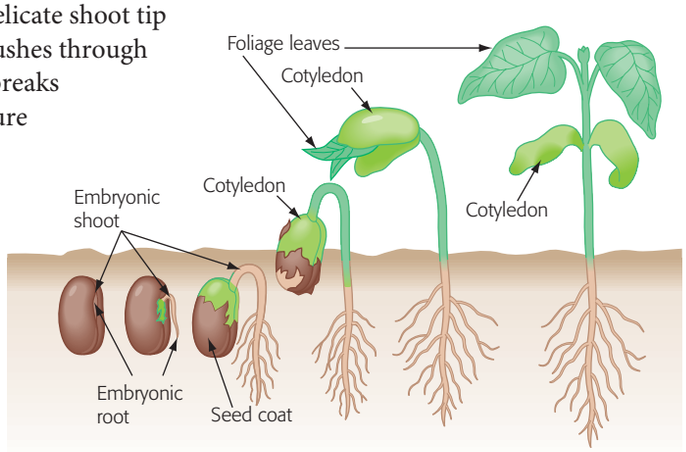
Dry fruits

Seed Germination

Germination of a seed usually begins when the seed takes up water. The hydrated seed expands, bursting its coat, and the embryo resumes the growth and development that was temporarily suspended during seed dormancy.

Figure 28.27 traces the germination of a garden bean. The embryonic root of the bean emerges first and grows downward from the germinating seed. Next, the embryonic shoot emerges, and a hook forms near its tip. The hook protects the delicate shoot tip by holding it downward as it pushes through the abrasive soil. As the shoot breaks through the soil surface, exposure to light stimulates the hook to straighten, and the tip is lifted. The first foliage leaves then expand from the shoot tip and begin making food for the plant by photosynthesis.

A germinating seed is fragile. In the wild, only a small fraction of seedlings endure long enough to reproduce. The great numbers of seeds produced by most plants compensate for the odds against each seedling, increasing the chances of reproductive success. ☑





► **Figure 28.27** **Germination in a garden bean.** After a seed takes up water, it bursts out of its coat and begins to grow.

☑ CHECKPOINT

Is the garden bean shown in Figure 28.27 a monocot or a eudicot?

Answer: It's a eudicot. (You can tell because it has two cotyledon leaves.)



Agriculture and People EVOLUTION CONNECTION

The Problem of the Disappearing Bees

Throughout this chapter, we've discussed how flowering plants and land animals have had mutually beneficial relationships throughout their evolutionary history. You've learned that most angiosperms depend on insects, birds, or mammals for pollination and seed dispersal. And most land animals depend on angiosperms for food and shelter. Such mutual dependencies tend to improve the reproductive success of both the plants and the animals and are thus favored by natural selection.

The flowers of many angiosperms attract pollinators that rely entirely on the flowers' nectar (a sugary fluid) and pollen for food. Evolutionary adaptations for advertising the presence of nectar include flower color and fragrance, which are keyed to pollinators' senses of sight and smell. For example, many flowers pollinated by birds are red or pink, colors to which bird eyes are especially sensitive. Flowers may also have markings that attract pollinators, leading them past pollen-bearing organs on their way to gathering nectar **(Figure 28.28)**. For example, flowers pollinated by bees often have markings that reflect ultraviolet light. Such markings are invisible to us, but vivid to bees. Many other animals—including hummingbirds, butterflies, and fruit bats—have similar relationships with other flower species. To a large extent, flowering plants are as diverse and successful as they are today because of their close connections with animals.

The importance of such interactions has been underscored by concern over colony collapse disorder. In late 2006, U.S. beekeepers noticed a sudden and drastic die-off in their bee colonies. The next year, similar problems were reported in Europe. Agricultural scientists fear that a shortage of bees could have devastating consequences on many food staples that require bees for pollination, such as almonds, berries, and fruits. Bees pollinate $15 billion worth of crops each year, and an estimated one-third of our food supply relies on bees. The cause of the die-off has not yet been explained, although several biological agents—such as mites or their pathogens—have been implicated. This much is certain: Colony collapse disorder is yet another reminder of how much we all depend on plants for our survival.

▼ **Figure 28.28** **A busy bee.**



Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

The Structure and Function of a Flowering Plant

Flowering plants, or angiosperms, account for nearly 90% of the plant kingdom.

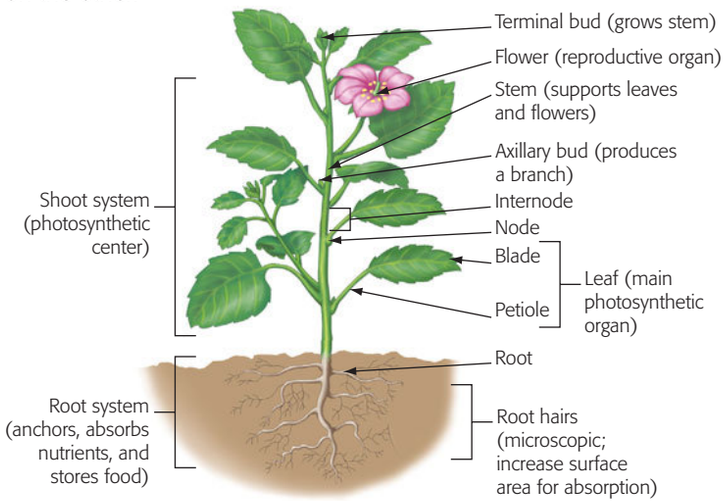
Monocots and Dicots

Angiosperms can be grouped into two categories based on the number of cotyledons (seed leaves) found in the embryo and other structural differences. Most dicots are eudicots.

Plant Structures					
	Seed leaves	**Leaf veins**	**Vascular bundles**	**Floral parts**	**Roots**
Monocots	One cotyledon	Parallel	Scattered	Multiples of three	Fibrous
Eudicots	Two cotyledons	Branched	Ring	Multiples of four or five	Taproot

Plant Organs: Roots, Stems, and Leaves

A plant body consists of a root system and a shoot system, each dependent on the other.



A growing shoot often lengthens only at the terminal bud; its axillary buds are dormant. This condition is called apical dominance and allows the plant to grow tall quickly.

Plant Tissues and Tissue Systems

Roots, stems, and leaves are made up of tissues organized into three tissue systems: the dermal tissue system, the vascular tissue system, and the ground tissue system.

The Three Tissues of Plant Organs

Dermal Tissue System	Vascular Tissue System	Ground Tissue System
• Functions in protection • Includes the epidermis, an outer layer that covers and protects the plant • Stomata (each surrounded by two guard cells): pores that regulate gas exchange between the cells of the leaf and the environment	• Functions in support and transport • Xylem: transports water and dissolved minerals • Phloem: transports sugars	• Functions mainly in storage • Includes leaf mesophyll, where most photosynthesis occurs

Plant Cells

Plant cells are distinguished by the presence of chloroplasts, a large central vacuole, and cell walls. There are several types of plant cells: parenchyma cells, collenchyma cells, sclerenchyma cells, water-conducting cells (tracheids and vessel elements), and food-conducting cells.

Plant Growth

Most plants display indeterminate growth, growing as long as they are alive. Some plants grow, reproduce, and die in one year (annuals); some live for two years (biennials); and some live for many years (perennials).

Primary Growth: Lengthening

Plant growth originates in meristems, areas of undifferentiated, dividing cells. Apical meristems are located at the tips of roots and in the terminal and axillary buds of shoots. These meristems initiate lengthwise growth by producing new cells. A root or shoot lengthens further as the new cells elongate. This cell division and elongation is called primary growth. The new cells eventually differentiate into specialized tissues.

Secondary Growth: Thickening

An increase in a plant's girth, called secondary growth, arises from cell division in a cylindrical meristem called the vascular cambium. The vascular cambium produces layers of secondary xylem, or wood, next to its inner surface. Outside the vascular cambium is bark, which consists of secondary phloem, a meristem called the cork cambium, and cork cells produced by the cork cambium. The outer layers of bark are sloughed off as the plant thickens.

The Life Cycle of a Flowering Plant

Many flowering plants can reproduce both asexually and sexually.

The Flower

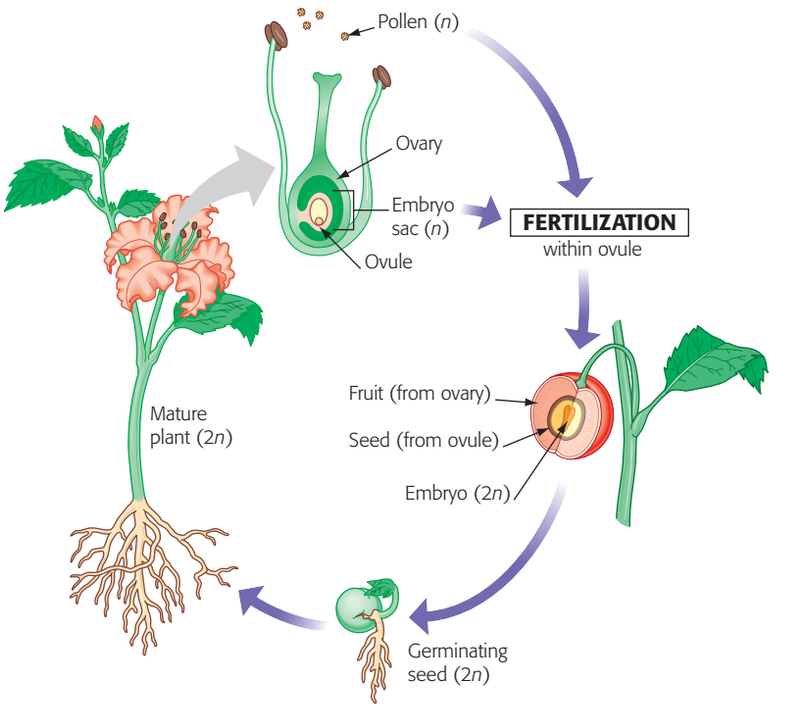
In angiosperms, the flower is the structure specific to sexual reproduction. The stamen contains the anther, in which pollen grains are produced. The carpel contains the stigma, which receives pollen, and the ovary, which contains the ovule.

Overview of the Flowering Plant Life Cycle

The plant life cycle alternates between diploid ($2n$) and haploid (n) generations. The spores in the anthers give rise to male gametophytes, or pollen grains, each of which produces two sperm. A spore in an ovule produces the female gametophyte, called an embryo sac. Each embryo sac contains an egg cell.

Pollination and Fertilization

After pollen lands on the stigma (pollination), the sperm pass down the stigma into the ovule. One sperm combines with the egg and the other combines with a second, diploid cell. This process, called double fertilization, is unique to plants.



Seed Formation

After fertilization, the ovule becomes a seed, and the fertilized egg within it divides to become an embryo. The other fertilized cell (now triploid) develops into the endosperm, which stores food for the embryo. A tough seed coat protects the embryo and endosperm. The embryo develops cotyledons (seed leaves), which absorb food from the endosperm.

Fruit Formation

While the ovule becomes a seed, the ovary develops into a fruit, which helps protect and disperse the seeds.

Seed Germination

A seed starts to germinate when it takes up water, expands, and bursts its seed coat. The embryo resumes growth, an embryonic root emerges, and a shoot pushes upward and expands its leaves.

SELF-QUIZ

1. While walking in the woods, you encounter an unfamiliar flowering plant. Which of the following plant features would help you determine whether that plant is a monocot or a eudicot? (Choose all that are appropriate.)
- **a.** size of the plant
- **b.** number of seed leaves
- **c.** shape of its root system
- **d.** number of petals in its flowers
- **e.** arrangement of vascular bundles in its stem
- **f.** whether or not it produces seed-bearing cones

2. Your friend plants a new herb (which is a eudicot and a perennial). During the first year, she allows the plants to grow naturally. Her plants grow tall and relatively spindly during the growing season, and when it comes time to harvest, she doesn't have a large yield. What phenomenon is responsible for her poor yield? What could your friend do to increase her yield next year?

3. A pea pod is formed from a(n) _____. A pea inside the pod is formed from a(n) _____.

4. Match each flower structure with its function.

a. pollen grain	**1.** attracts pollinators
b. ovule	**2.** develops into seed
c. anther	**3.** protects an unopened flower
d. ovary	**4.** produces sperm
e. sepal	**5.** produces pollen
f. petal	**6.** contains ovules

5. Many plant species can reproduce both sexually and asexually. Which mode of reproduction would generally be more advantageous in a location where the composition of the soil is changing rapidly? Why?

6. What part of a plant are you eating when you consume each of the following?
- **a.** tomato
- **b.** apple
- **c.** spinach
- **d.** sweet potato
- **e.** black bean

7. In the angiosperm life cycle, which of the following processes is directly dependent on meiosis?
- **a.** production of gametophytes
- **b.** production of gametes
- **c.** production of spores
- **d.** all of the above

8. In angiosperms, each pollen grain produces two sperm. What do these sperm do?
- **a.** Each one fertilizes a separate egg cell.
- **b.** One fertilizes an egg, and the other fertilizes the fruit.
- **c.** One fertilizes an egg, and the other is kept in reserve.
- **d.** Both fertilize a single egg cell.
- **e.** One fertilizes an egg, and the other fertilizes a cell that develops into stored food.

9. Which of the following is closest to the center of a woody stem? Which is farthest from the center?
- **a.** cork cambium
- **b.** primary xylem
- **c.** primary phloem
- **d.** secondary xylem
- **e.** secondary phloem

10. A gardener is concerned that his perennial plants are not growing well. He notes that the stems on his plants are not thickening adequately over the years. This suggests reduced activity of which plant tissue?

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

11. During a recent ice storm, many old trees were snapped by the weight of the ice. A botanist in the area would like to analyze the remains of the trees and determine how old they really were. Describe a procedure that could be used to determine the approximate age of the trees. Explain the basis of this method in terms of plant tissue growth.

12. Plants can alter the shape of their guard cells, thereby regulating the size of the stomata on their leaves. Stomata must be open to allow entrance of carbon dioxide, which is necessary for photosynthesis. During the summer, the stomata are often closed around noon, when the most sunlight is likely to reach the plant. Propose an explanation for why it may be advantageous for stomata to be closed when conditions seem optimal for photosynthesis. How could you test your hypothesis?

BIOLOGY AND SOCIETY

13. Tropical forests contain a wealth of plants that are potential new sources of food, medicine, and other useful products. As a result of growing populations and debt, however, many tropical forests in less industrialized countries are being cut for lumber and farmland, and many species are disappearing. More industrialized countries are pressuring the tropical countries to protect the forests before even more species are lost. Many people in the less industrialized nations see little incentive to preserve the forests only to have corporations from more industrialized countries profit from their products. Is there a way to preserve the tropical forests so that both the less industrialized and more industrialized nations will benefit from their abundance?

14. Cloning is a fiercely debated topic in our country. Most of the ethical debates concerning cloning center on the cloning of animals. There is not much talk about the cloning of plants. Do you have the same opinion about cloning plants and animals? Why or why not? Do you think that they should be similarly regulated? What unique problems might each present?

29 The Working Plant



Cleansing plants. This photo, taken about four months after the 2011 tsunami in northeastern Japan, shows sunflowers used to treat radioactive contamination.



CHAPTER CONTENTS

How Plants Acquire and Transport Nutrients 626

Plant Hormones 632

Response to Stimuli 636

CHAPTER THREAD

The Interdependence of Organisms

BIOLOGY AND SOCIETY
Planting Hope in the Wake of Disaster 625

THE PROCESS OF SCIENCE
Do Chemical Signals Affect Plant Growth? 633

EVOLUTION CONNECTION
Plants, Mantises, and People 637



Planting Hope in the Wake of Disaster

On March 11, 2011, a magnitude 9.0 earthquake originating beneath the Pacific Ocean produced a 100-foot tsunami that swept 6 miles into northeastern Japan. One of the five strongest earthquakes ever recorded, the disaster had far-reaching consequences, killing more than 15,000 people and damaging or destroying at least 125,000 buildings. After the surge of ocean water from the tsunami flooded the Fukushima Nuclear Power Plant, the resulting loss of power and failure of the backup cooling systems led to a reactor core meltdown. Fukushima joined the 1986 Chernobyl disaster in Ukraine as one of the worst nuclear accidents the world has ever seen.

The cleanup effort in Japan will take decades. In addition to bulldozers and wrecking crews, help is coming from a natural source: plants. The use of plants to help clean up polluted soil and groundwater is called phytoremediation. Phytoremediation is one type of bioremediation, the use of living organisms to detoxify polluted sites. Plants can efficiently move minerals and other compounds from the soil into the plant body. Usually, the absorbed compounds are nutrients that help the plant grow. But many species of plants are capable of absorbing large amounts of radioactive isotopes and heavy metals. Efforts are under way to plant millions of sunflowers in the Fukushima Prefecture to help restore the area. A similar effort continues today in New Orleans as a way to detoxify soil that was contaminated in the aftermath of Hurricane Katrina, which devastated the region in 2005.

Because crews cleaning up after such disasters have only to remove a few cubic meters of plant material rather than the thousands of cubic meters of soil that are actually contaminated, phytoremediation can be a cost-effective and efficient process. An added benefit: Using plants to clean the soil can detoxify an area without dramatically disturbing the landscape. And sunflowers—such as those shown on the left that were photographed near Natori, Japan—provide an uplifting message to the community, bringing beauty and life back to an area weary with grief and loss.

By using plants to clean up toxic wastes, we are benefiting from millions of years of plant evolution. Although plants are unable to move about in search of food, they have evolved an amazing ability to pull water and nutrients out of the soil and air. In this chapter, we'll see how plants obtain essential nutrients and how they transport them throughout their roots, stems, and leaves. Then we'll examine other aspects of the life of a working plant, including the crucial roles played by hormones and how certain plant activities are affected by stimuli from the environment. Throughout the discussion, we'll explore the theme of how different forms of life—such as plants and animals—depend on each other for survival within Earth's biosphere.

How Plants Acquire and Transport Nutrients

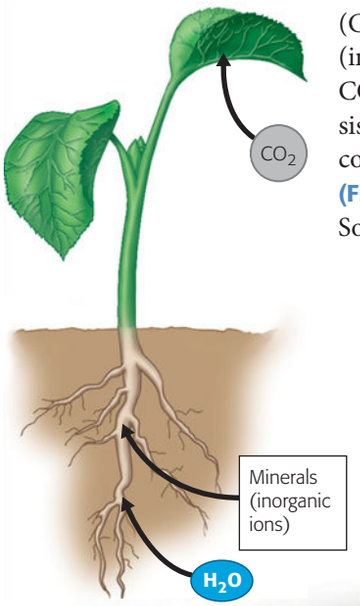


Figure 29.1 The uptake of nutrients by a plant. A plant absorbs the CO_2 it needs from the air and minerals and H_2O from the soil.

Watch a plant grow from a tiny seed and you can't help wondering where all the mass comes from. About 96% of a plant's dry weight is organic (carbon-containing) material synthesized from inorganic nutrients extracted from the surroundings. Plants obtain carbon dioxide (CO_2) from the air and water (H_2O) and **minerals** (inorganic ions) from the soil **(Figure 29.1)**. From the CO_2 and H_2O, plants produce sugars via photosynthesis. These sugars, combined with minerals, are used to construct all the other organic materials a plant needs **(Figure 29.2)**. Plants, like people, require a balanced diet. So let's start by discussing plant nutrition.

Plant Nutrition

A chemical element is considered an **essential element** if a plant must obtain it from its environment to complete its life cycle. Seventeen elements are essential to all plants, and a few others are essential to certain types of plants. Of the 17 essential elements, 9 are called **macronutrients** because plants require relatively large amounts of them. Elements that plants need in extremely small amounts are called **micronutrients**.

Macronutrients

Six of the nine macronutrients—carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus—make up almost 98% of a plant's dry weight. The other three macronutrients—calcium, potassium, and magnesium—make up another 1.5%.

What does a plant do with macronutrients? Carbon, oxygen, and hydrogen are the basic ingredients of a plant's organic compounds. Nitrogen is a component of all nucleic acids and proteins, as well as ATP, chlorophyll



Figure 29.2 A banyan tree is a giant product of photosynthesis. Plants use sugars created by photosynthesis to produce all the organic materials they need. The giant trunk and long branches of this tree consist largely of molecules derived from sugars.

(the key light-absorbing molecule in plants), and many plant hormones. Sulfur is a component of most proteins. Phosphorus is a major component of nucleic acids, phospholipids, and ATP. The other macronutrients, although present in smaller amounts, play similarly important roles. For example, magnesium is an essential component of chlorophyll.

Micronutrients

Eight micronutrients make up the remaining 0.5% of a plant's dry weight and are required by all plants. The eight micronutrients are iron, chlorine, copper, manganese, zinc, molybdenum, boron, and nickel. A plant recycles the atoms of micronutrients over and over, so it needs them in only minute quantities. Yet a deficiency of any micronutrient can kill a plant.

Fertilizers

The quality of soil, especially the availability of nutrients, affects the health of plants and, for plants we consume, the quality of our own nutrition ("You are what you eat!"). Nitrogen shortage is the most common nutritional problem for plants **(Figure 29.3)**. Nitrogen-deficient crop plants may produce grain, but the grain will have a lower nutritional value, and its nutrient deficiencies will be passed on to livestock or human consumers.

Fertilizers are compounds given to plants via the soil to promote the plants' growth. There are two basic types of fertilizers: inorganic and organic. Inorganic fertilizers contain simple inorganic minerals, such as mined limestone (rich in calcium) or phosphate rock. Inorganic fertilizers come in a wide variety of formulations, but most emphasize the "N-P-K ratio," the relative amounts of the three nutrients most often deficient in depleted soils: nitrogen (N), phosphorus (P), and potassium (K). An all-purpose fertilizer, for example, might be "5-5-5," with 5% of each of these vital nutrients.

Organic fertilizers are composed of chemically complex organic matter such as **compost**, a soil-like mixture of decomposed organic matter. Many gardeners maintain a free-standing compost pile or an enclosed compost bin to which they add leaves, grass clippings, yard waste, and kitchen scraps (avoiding meat, fat, and bones). Over time, the vegetable matter is broken down by microbes, fungi, and animals **(Figure 29.4)**. Occasional turning and watering speeds the process. The compost, which is highly valued by gardeners for its nutrient-rich composition, can be applied to outdoor gardens or indoor pots.

Compost and other organic fertilizers are a key to **organic farming**. Organic farmers follow guidelines that promote sustainable agriculture—a system of farming that protects biological diversity, maintains and replenishes soil quality (as by crop rotation), manages pests with no (or few) synthetic pesticides, avoids genetically modified organisms, conserves water, and uses no (or few) synthetic fertilizers. In the United States, organic farming is one of the fastest-growing segments of agriculture, but organic farms still account for fewer than 1% of total agricultural acreage. ☑



►**Figure 29.3 The effect of nitrogen shortage.** These images contrast a normal buckwheat plant (left) with one that was grown in nitrogen-poor conditions (right). Nitrogen-deficient plants can be diagnosed by stunted growth and leaves that turn yellow starting at the tips.

▼**Figure 29.4 Compost.** Steam is produced by the metabolic activity of naturally occurring organisms that break down the organic matter of rotting vegetation.



☑ CHECKPOINT

What inorganic nutrients do plants acquire from the air? What nutrients do plants extract from the soil?

Answer: carbon dioxide; water and minerals (inorganic ions)

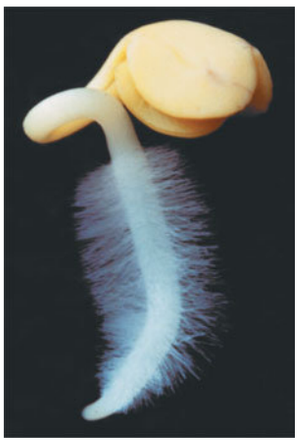
From the Soil into the Roots

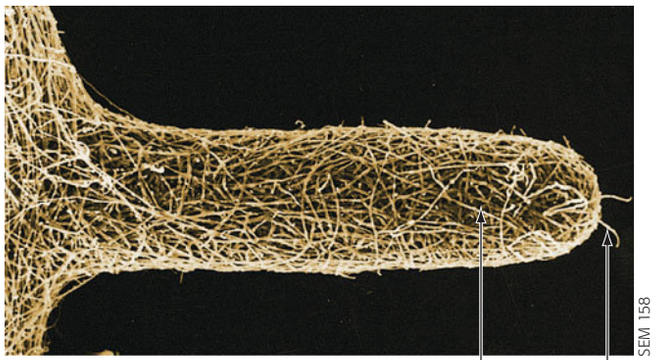
Plant roots have a remarkable capacity for absorbing water and essential nutrients from soil because of their root hairs, extensions of epidermal cells that dramatically increase the surface area available for absorption (Figure 29.5). For example, the root hairs of a single sunflower plant, if laid end to end, could stretch many miles, providing a huge surface area in contact with nutrient-containing soil.

All substances that enter a plant root are dissolved in water. To be transported, water and solutes must move from the soil through the epidermis and cortex of the root, then into the water-conducting xylem tissue in the root's central cylinder (see Figure 28.8). To reach the xylem, the solution must pass through the plasma membranes of root cells. Because these membranes are selectively permeable, only certain solutes reach the xylem. This selectivity helps regulate the mineral composition of a plant's vascular system.

Many plants gain significant surface area for absorption through symbiotic associations with fungi. Together, the plant's roots and the associated fungus form a mutually beneficial (mutualistic) structure called a **mycorrhiza** (plural, *mycorrhizae*) (Figure 29.6). Fungal filaments around the roots absorb water and minerals much more rapidly than can the roots alone. Some of the water and minerals taken up by the fungus are transferred to the plant, and the plant's photosynthetic products nourish the fungus.

▼ **Figure 29.5 Root hairs that enable efficient absorption.** The root hairs of a plant, clearly visible in this photograph of a radish seedling, are extensions of epidermal cells on the outer surface of the root.





▲ **Figure 29.6 A mycorrhiza.** This micrograph shows a small root of a eucalyptus tree covered with a twisted mat of fungal filaments.

The Role of Bacteria in Nitrogen Nutrition

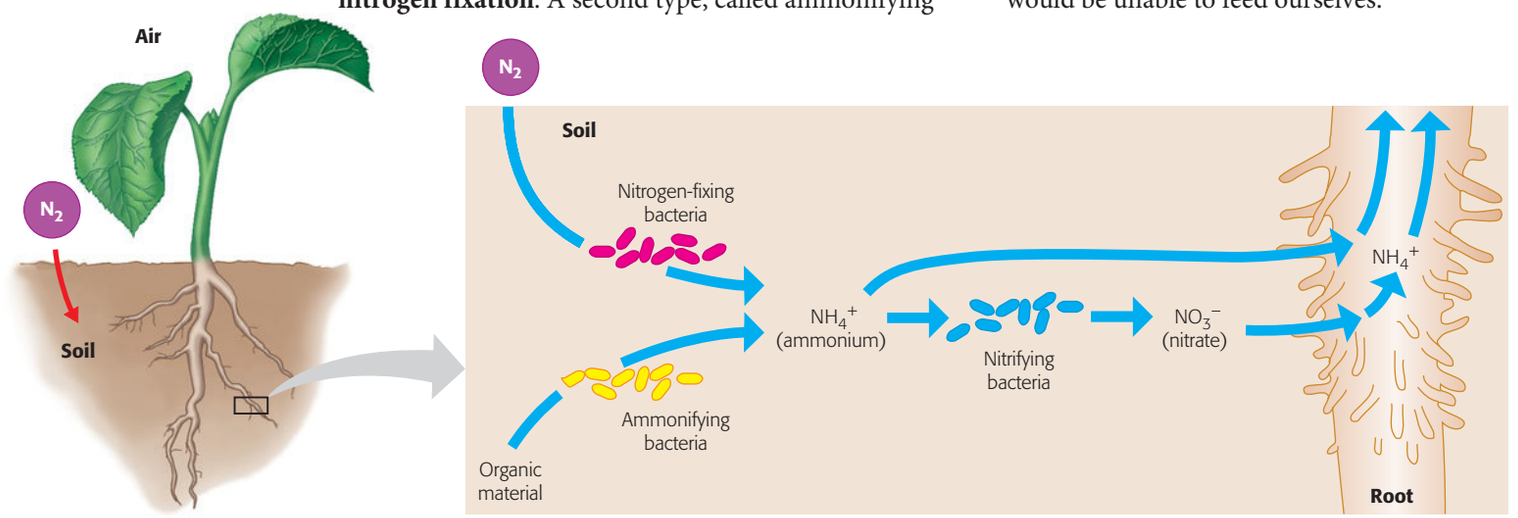
Air penetrates the soil around roots, but plants cannot use the form of nitrogen found in air—gaseous N_2. For plants to absorb nitrogen from the soil, N_2 must first be converted to ammonium (NH_4^+) or nitrate (NO_3^-). Most plants rely on bacteria for these conversions.

In what way do farmers depend on bacteria?

Soil Bacteria and Nitrogen

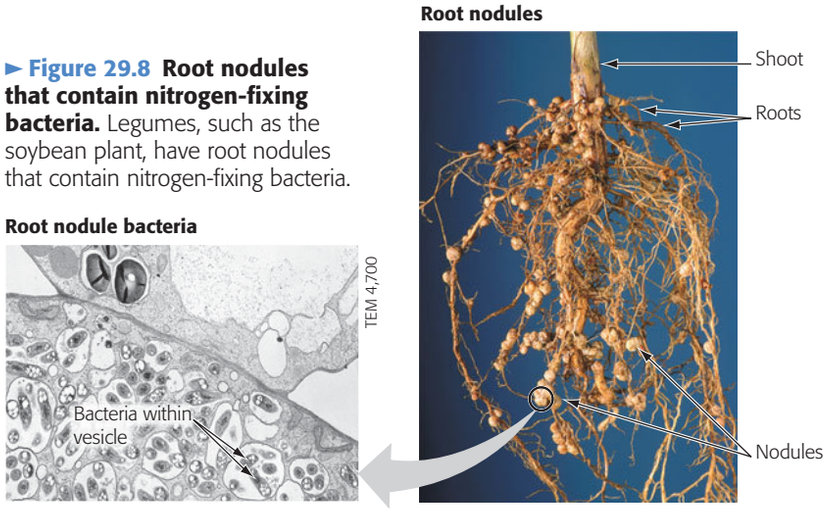
Figure 29.7 shows three types of soil bacteria that play essential roles in supplying plants with nitrogen. One type, called nitrogen-fixing bacteria (), converts atmospheric N_2 to ammonium, a process called **nitrogen fixation**. A second type, called ammonifying bacteria (), adds to the soil's supply of ammonium by decomposing organic matter. A third type of soil bacteria, called nitrifying bacteria (), converts soil ammonium to nitrate. Plants take up most of their nitrogen in this form. They then convert nitrate back to ammonium, which plants can incorporate into proteins and other nitrogen-containing organic molecules. Although we often think of bacteria as troublesome (particularly when they infect us), it is important to note that our lives utterly depend on bacteria: Without bacteria, our crop plants could not obtain sufficient nitrogen, and we would be unable to feed ourselves.

▼ **Figure 29.7 The role of bacteria in supplying nitrogen to plants.**



Root Nodule Bacteria and Nitrogen

Some plant families, including legumes—peas, beans, peanuts, and many other plants that produce their seeds in pods—have their own built-in source of ammonium: nitrogen-fixing bacteria that live in swellings called root nodules (Figure 29.8). Within these nodules, plant cells have been "infected" by nitrogen-fixing bacteria that reside inside cytoplasmic vesicles. The symbiotic relationship between a plant and its nitrogen-fixing bacteria is mutually beneficial ("You scratch my back, I'll scratch yours"). The bacteria have enzymes that help convert atmospheric N_2 to ammonium (NH_4^+), a form readily used by the plant; the plant, in turn, provides the bacteria with other nutrients. When conditions are favorable, root nodule bacteria fix so much nitrogen that the nodules secrete excess ammonia, which improves the soil. This is one reason farmers practice crop rotation, one year planting a nonlegume such as corn and the next year planting a legume such as soybeans. The legume crops may be plowed under to decompose into "green manure," reducing the need for fertilizer. ☑



► **Figure 29.8 Root nodules that contain nitrogen-fixing bacteria.** Legumes, such as the soybean plant, have root nodules that contain nitrogen-fixing bacteria.

☑ CHECKPOINT

Why might a pollutant that kills soil bacteria result in nitrogen deficiency in plants?

Answer: because certain soil bacteria make nitrogen available to plants in forms they can use

The Transport of Water

As a plant grows upward toward sunlight, it needs an increasing supply of resources from the soil. Imagine hauling a 5-gallon bucket of water up five flights of stairs every 20 minutes, all day long. To thrive, a typical tree must transport that quantity of water from its roots to the rest of the plant.

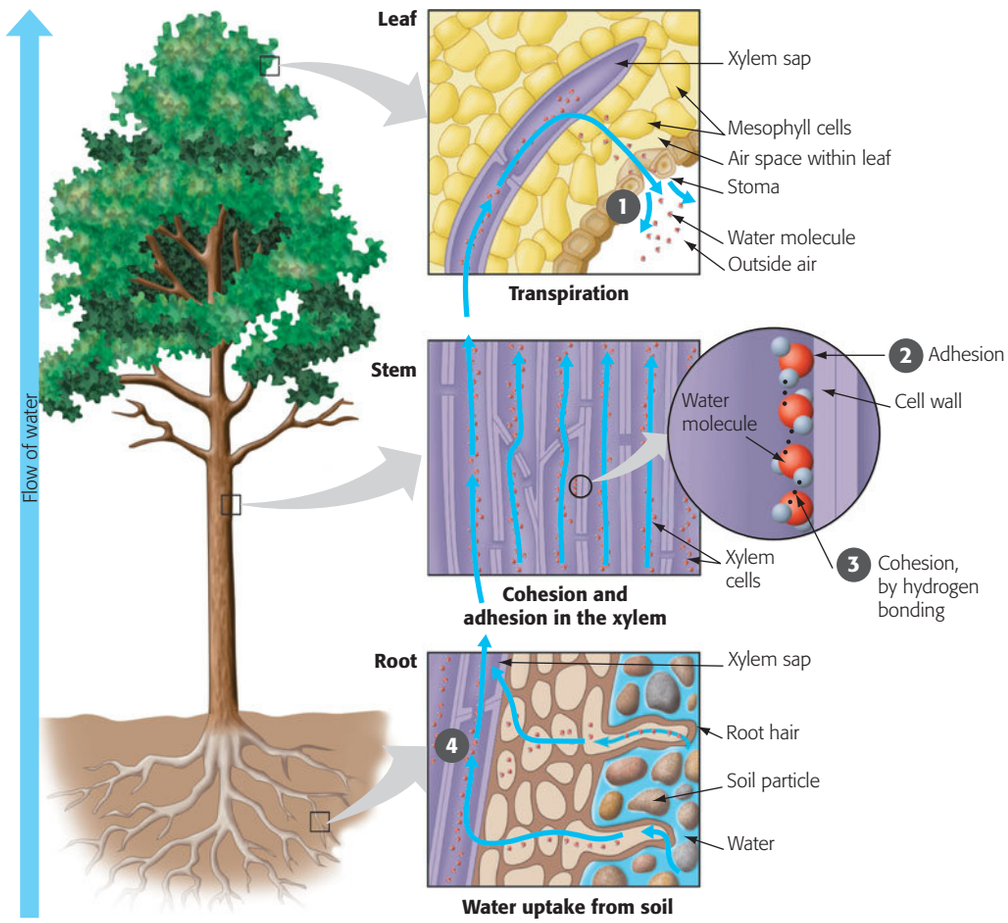
As discussed in Chapter 28, mature water-conducting cells of the xylem are arranged end to end to form very thin vertical tubes (see Figure 28.11). A solution of water and inorganic nutrients, called **xylem sap**, flows through these tubes all the way from a plant's roots to the tips of its leaves. Let's look at how this sap is moved through the body of the plant.

The Ascent of Xylem Sap

What force moves xylem sap up against the downward pull of gravity? For the most part, xylem sap is pulled upward by **transpiration**, the loss of water from the leaves of a plant by evaporation (Figure 29.9). Most transpiration occurs through the stomata of leaves. The stomata open into air spaces, which are filled with water molecules that have evaporated from the surrounding mesophyll cells. ❶ Water vapor diffuses out of the stomata because the surrounding air is usually drier than the inside of the leaf.

Transpiration can pull xylem sap up a tree because of two special properties of water: cohesion and adhesion. **Adhesion** is the sticking together of molecules of different kinds. ❷ Water molecules tend to adhere to cellulose molecules in the walls of xylem cells. **Cohesion** is the sticking

▼ **Figure 29.9 How transpiration pulls water up the xylem of a tree.**





together of molecules of the same kind. ❸ In the case of water, hydrogen bonds make the H_2O molecules stick to one another (see Figure 2.9). ❹ Together, adhesion and cohesion create a continuous string of water molecules running from the roots to the leaves. These molecules stick to each other and to the inside walls of the xylem tubes.

Before a water molecule can exit the leaf, it must break off from the top of the string. In effect, the water molecule is pulled off by a concentration gradient: The air outside the leaf is much drier than the moist interior of the leaf, causing the water molecule to diffuse outward. Cohesion resists this pulling force (because water molecules are attracted to each other and so don't want to separate) but is not strong enough to overcome the force of evaporation. The molecule breaks off, and the opposing forces of cohesion and transpiration put tension on the rest of the string of water molecules. As long as transpiration continues, the string is kept tense and is pulled upward as one molecule exits the leaf and the one behind it is tugged up into its place. Water molecules are thus pulled upward by this string, one at a time. Biologists call this explanation for the ascent of xylem sap the **transpiration-cohesion-tension mechanism**. Transpiration exerts a pull on a tense, unbroken string of water molecules that is held together by cohesion and helped upward by adhesion.

Note that the transport of xylem sap requires no energy expenditure by the plant; a plant has no muscles for pumping. Physical properties—cohesion, adhesion, and the evaporating effect of the sun—move water and dissolved minerals from a plant's roots to its shoots. Transpiration is thus a highly efficient means of moving a lot of water upward through the body of a plant.

You have probably tasted xylem sap moved via transpiration yourself. When maple trees resume growth in the spring after a leafless winter, starch that was produced the previous summer and stored in the roots is converted to sugar, which is transported upward in the xylem sap via transpiration to nourish the developing leaf buds. This sap can be harvested in buckets and boiled to concentrate the sugar. It takes about 50 gallons of sap to make one gallon of maple syrup.

The Regulation of Transpiration by Stomata

Although necessary to distribute water, transpiration also works against plants because it can result in the loss of an astonishing amount of water. Transpiration is usually greatest on days that are sunny, warm, dry, and windy, because these weather conditions increase evaporation. An average-sized maple tree (about 20 m high) can lose more than 200 L of water per hour during a summer day. As long as water moves up from the soil fast enough to replace the lost water, this presents no problem. But if the soil dries out and transpiration exceeds the delivery of water, the leaves will wilt. Unless the soil and leaves are rehydrated, the plant will eventually die.

Why are plants more likely to wilt on windy days?

The leaf stomata, which can open and close, are evolutionary adaptations that help plants adjust their transpiration rates to changing environmental conditions. In many plants, stomata are open during the day, which allows CO_2 to enter the leaf from the atmosphere and thus keep photosynthesis going when sunlight is available. However, the plant also loses water through transpiration. At night, when there is no light for photosynthesis and therefore no need for CO_2, many plants close their stomata, saving water. Stomata may also close during the day if a plant is losing water too fast. The opening and closing of stomata is controlled by the changing shape of the two guard cells flanking each stoma **(Figure 29.10)**. ☑

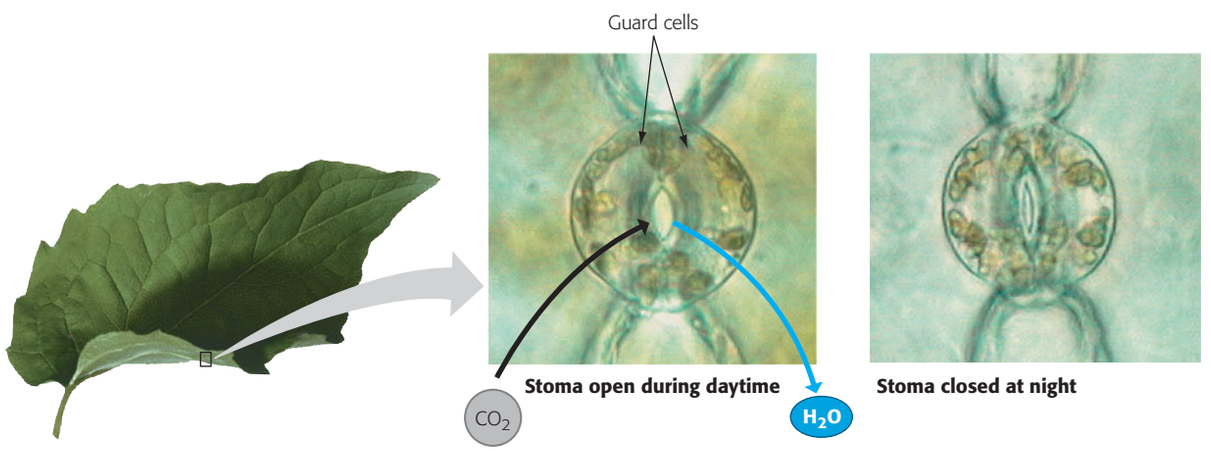
The Transport of Sugars

A plant's survival depends not only on the transport of water and minerals absorbed from the soil but also on the transport of the sugars it makes by photosynthesis. This is the main function of phloem.

☑ CHECKPOINT

1. Water moves from the roots to the tips of the leaves without any expenditure of energy by the plant. What is this process called? What two forces between molecules are responsible?
2. What is the evolutionary advantage of stomata that close at night?

Answers: **1.** *transpiration; cohesion and adhesion* **2.** *Closed stomata prevent water loss when photosynthesis cannot occur.*



► **Figure 29.10 How stomata control transpiration via guard cells.** A pair of guard cells (each the shape of a half-circle) surrounding a stoma can change shape in response to environmental signals, regulating the rate of transpiration and CO_2 uptake.

Phloem consists of living food-conducting cells arranged end to end into long tubes. Through perforations in the end walls of these cells, sugary liquid called **phloem sap** moves freely from one cell to the next (Figure 29.11). Phloem sap contains inorganic ions, amino acids, and hormones in transit from one part of the plant to another, but its main solute is usually the disaccharide sugar sucrose (table sugar).

In contrast to xylem sap, which only flows upward from the roots, phloem sap moves throughout the plant in various directions. A location in a plant where sugar is being produced (either by photosynthesis or by the breakdown of stored starch) is called a **sugar source**. A receiving location in the plant, where the sugar will be stored or consumed, is called a **sugar sink**. Sugar moves within food-conducting tubes of phloem from a source, such as a leaf, to a sink, such as a root or a fruit.

What causes phloem sap to flow from a source to a sink? Figure 29.12 uses a beet plant to illustrate a widely accepted model called the **pressure-flow mechanism**. At the sugar source (the beet leaves), 1 sugar is loaded from a photosynthetic cell into a phloem tube via active transport. Sugar loading at the source end raises the solute (sugar) concentration inside the phloem tube. 2 The high solute concentration draws water into the tube by osmosis, usually from the xylem. The flow of water from the xylem into the phloem raises the water pressure at the source end of the phloem tube.

At the sugar sink (the beet root), both sugar and water leave the phloem tube. 3 As sugar leaves the phloem, lowering the sugar concentration at the sink end, 4 water moves by osmosis back into the xylem. The exit of water lowers the water pressure in the tube.

The building of water pressure at the source end of the phloem tube and the reduction of water pressure at the sink end cause phloem sap to flow from source to sink. This pressure-flow mechanism explains why phloem sap always flows from a sugar source to a sugar sink, regardless of their locations in the plant.

We now have a broad picture of how a plant absorbs substances from the soil and transports materials from one part of its body to another: Water and inorganic ions enter from the soil and are pulled upward through xylem by transpiration. Carbon dioxide enters leaves through the stomata and is incorporated into sugars, which are distributed by phloem. Pressure flow drives the phloem sap from leaves and storage sites to other parts of the plant, where the sugars are used or stored. In the next section, we'll consider various ways that a working plant uses these resources. ✓

✓ CHECKPOINT

In the pressure-flow mechanism, phloem sap always flows from a _____ to a _____.

Answer: sugar source; sugar sink

Figure 29.11 Food-conducting cells of phloem. The main function of phloem is to transport sugars through living food-conducting cells arranged into tubes. Phloem sap moves through openings between the cells.

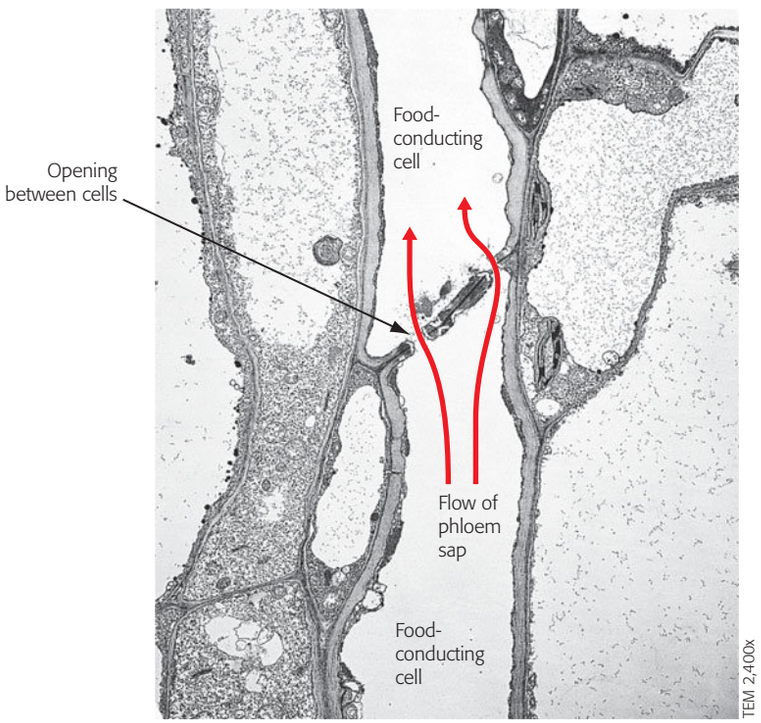
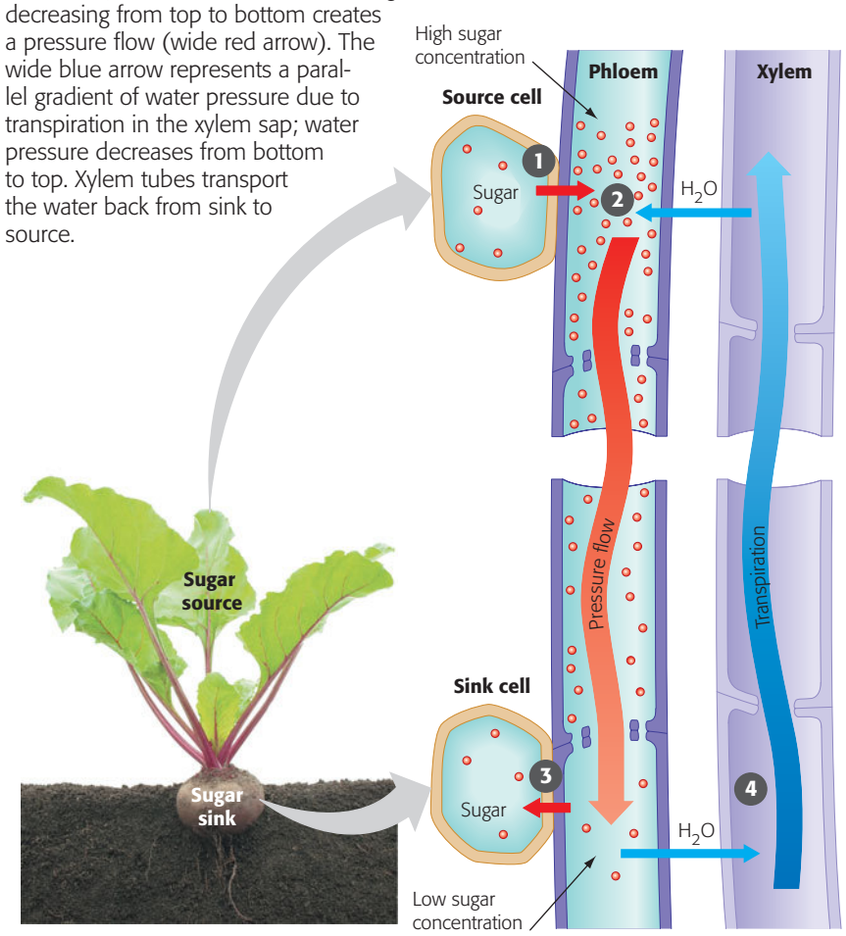


Figure 29.12 Pressure flow in plant phloem. The red dots in the phloem tube represent sugar molecules; notice that a concentration gradient decreasing from top to bottom creates a pressure flow (wide red arrow). The wide blue arrow represents a parallel gradient of water pressure due to transpiration in the xylem sap; water pressure decreases from bottom to top. Xylem tubes transport the water back from sink to source.



Plant Hormones

A **hormone** is a chemical signal produced in one part of an organism and transported to other parts, where it acts on target cells to change their functioning (see Chapter 25). Plants produce hormones in very small amounts, but even a tiny amount of any of these chemicals can have profound effects on growth and development. As they do in people, hormones in plants control growth and development by affecting the division, elongation, and differentiation of cells.

Plant biologists have identified five major types of plant hormones, which are listed in **Table 29.1**. Each type of hormone can produce a variety of effects, depending on the species and developmental stage of the plant as well as the hormone's concentration and site of action. In most situations, a plant hormone does not act alone. Instead, it is the relative concentration of two or more hormones that controls a plant's growth and development.



▲ **Figure 29.13 Sunflowers growing toward light.** Phototropism guides growing plants toward the sunlight needed for photosynthesis.

Auxins

A group of related hormones called **auxins** are responsible for a wide range of growth and development effects in plants. One of the main effects of auxins is to promote the elongation of cells.

Phototropism and Cell Elongation

Phototropism is the directional growth of a plant shoot in response to light. For example, a sunflower will rotate its flower and grow toward sunlight **(Figure 29.13)**. And houseplants on a windowsill will tend to grow toward the sunlight in the window. Phototropism directs both growing seedlings and the shoots of mature plants toward the sunlight they use for photosynthesis.

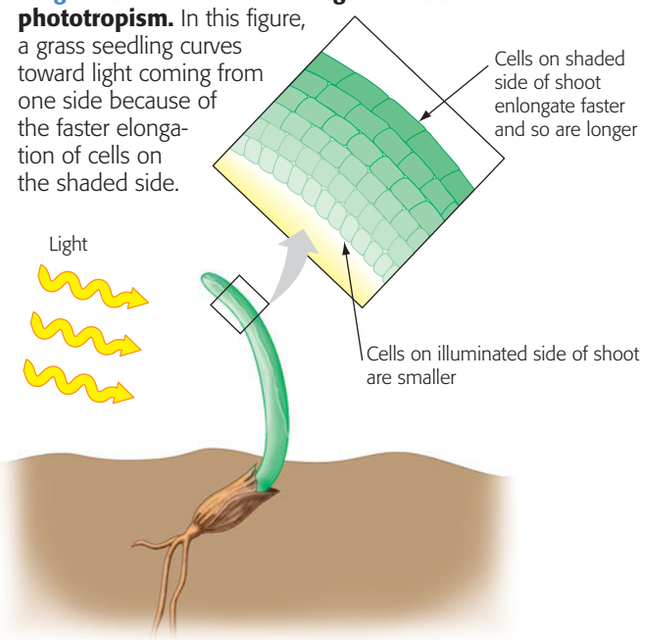
How does a plant grow in a particular direction? Microscopic observations of growing plants reveal the cellular mechanism that underlies phototropism **(Figure 29.14)**. Cells on the side of a stem that gets the least amount of light are larger—actually, they have elongated faster—than those on the brighter side, causing the shoot to bend toward the light. If a seedling is illuminated uniformly from all sides or if it is kept in the dark, the cells all elongate at a similar rate and the seedling grows straight upward.

What causes plant cells on the dark side of a shoot to grow faster than those on the bright side? Our present understanding of this phenomenon emerged from a series of classic experiments conducted by two scientists with a very familiar name, as we see next.

Table 29.1 Major Types of Plant Hormones

Hormone	Major Functions	Where Produced or Found in Plant
Auxins	Stimulate stem elongation; affect root growth, differentiation, and branching; stimulate development of fruit, apical dominance, phototropism, and gravitropism	Meristems of apical buds, young leaves, embryos within seeds
Ethylene	Promotes fruit ripening; opposes some auxin effects; promotes or inhibits growth and development of roots, leaves, and flowers, depending on species	Ripening fruit, nodes of stems, aging leaves and flowers
Cytokinins	Affect root growth and differentiation; stimulate cell division and growth; stimulate germination; delay aging	Made in roots and transported to other organs
Gibberellins	Promote seed germination, bud development, stem elongation, and leaf growth; stimulate flowering and fruit development; affect root growth and differentiation	Meristems of apical buds and roots, young leaves, embryos
Abscisic acid	Inhibits growth; closes stomata when water is scarce; helps maintain dormancy	Leaves, stems, roots, green fruit

▼ **Figure 29.14 How cell elongation causes phototropism.** In this figure, a grass seedling curves toward light coming from one side because of the faster elongation of cells on the shaded side.

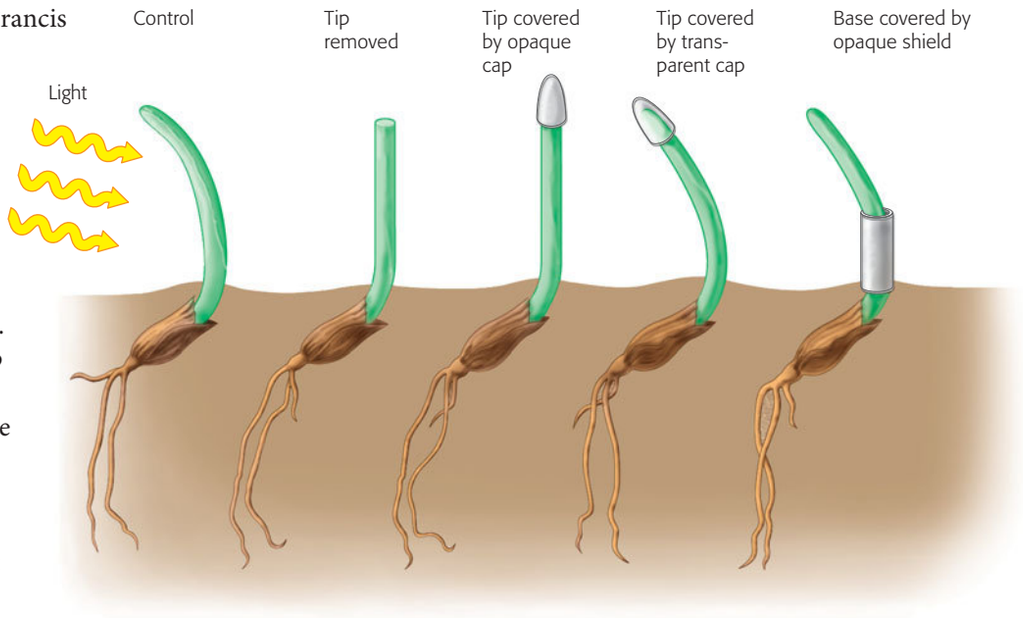


Do Chemical Signals Affect Plant Growth?

In the late 1800s, Charles Darwin and his son Francis performed some of the earliest experiments on phototropism **(Figure 29.15)**. They began with the **observation** that grass seedlings bent toward light only if the tips of their shoots were present. This led them to **question** whether the tips of the seedlings produced some kind of chemical growth signal. Their **hypothesis** was that the plant tips sensed light and produced a growth signal in response. They made a **prediction**: Removing a shoot tip or blocking its access to light would prevent phototropism. Several of their **experiments** are summarized in Figure 29.15.

The Darwins' **results** showed that removing the tip of a grass shoot did prevent growth toward light. The shoot also remained straight when they placed an opaque cap on its tip. However, the shoot curved normally when they placed a transparent cap on its tip or an opaque shield around its base. The Darwins concluded that the tip of the shoot was responsible for sensing light. They also recognized that the growth response, the bending of the shoot, occurred below the tip. Therefore, they speculated that some unknown growth signal was transmitted downward from the tip to the growing region of the shoot.

Building on the Darwins' results, botanists have since discovered the mechanisms of many other plant hormones. This understanding is one of the cornerstones of modern agriculture, allowing people to control the growth of plants in a variety of ways.



▲ **Figure 29.15 The Darwins' classic experiments on phototropism.** This figure summarizes experiments conducted by Charles Darwin and his son Francis. Together, these results suggested that a substance produced by the tip of a seedling controls phototropism.

The Action of Auxins

The hormones responsible for the phototropism observed by the Darwins are auxins produced by the apical meristem at the tip of a shoot. Illuminating one side of a shoot results in a concentration of auxin in the cells on the dark side. This uneven distribution of auxins makes cells on the dark side elongate, causing the shoot to bend.

Auxins promote cell elongation in stems only when they are present within a certain concentration range. Interestingly, this same concentration range inhibits cell elongation in roots. Above this range, auxins inhibit cell elongation in stems; and below this range, they cause root cells to elongate. This complex set of effects reinforces two points: (1) The same hormone may have different effects at different concentrations in the same target cell, and (2) a particular concentration of a hormone may have different effects on different target cells.

In addition to causing stems and roots to lengthen, auxins promote growth in stem diameter. Furthermore, auxins made in developing seeds promote the growth of fruit. Farmers sometimes produce seedless tomatoes, cucumbers, and eggplants by spraying unpollinated plants with synthetic auxins.

The discovery of plant hormones has produced many advances in agriculture. The use of synthetic plant hormones allows more food to be produced at lower cost. For example, one of the most widely used herbicides, or weed killers, is a synthetic auxin that disrupts the normal balance of hormones that regulate plant growth. Because dicots are more sensitive than monocots to this herbicide, it can be used to selectively remove dandelions and other unwanted broadleaf dicot weeds from a monocot lawn or field of grain. By applying herbicides to cropland, a farmer can reduce the amount of plowing required to control weeds, thus reducing soil erosion, fuel consumption, and labor costs.

At the same time, there is growing concern that the heavy use of artificial chemicals in food production may pose environmental and health hazards. Also, many consumers are concerned that foods produced using artificial hormones may not be as tasty or nutritious as those raised naturally. This highlights an important question about modern agricultural techniques: Should we continue to produce cheap, plentiful food using artificial chemicals and tolerate the potential problems; or should we put more of our agricultural effort into organic farming, recognizing that foods may be less plentiful and more expensive as a result? This is something you need to consider as you make choices about the foods you buy and eat. ☑

☑ CHECKPOINT

Plants have a tendency to bend toward the light. What is this tendency called? Which group of hormones promotes this tendency by causing cell elongation in the plant?

Answer: phototropism; auxins

Ethylene

Ethylene is a hormone, released as a gas, that triggers a variety of aging responses in plants, including fruit ripening and dropping of leaves.

Fruit Ripening

A burst of ethylene production in a fruit triggers its ripening. Because ethylene is a gas, the signal to ripen spreads from fruit to fruit: One bad apple really can spoil the bunch! You can make fruit ripen faster if you store it with already ripened fruit in a bag so that the ethylene gas accumulates **(Figure 29.16)**. On a commercial scale, many kinds of fruit—tomatoes, for instance—are often picked green and then partially ripened in huge storage bins into which ethylene gas is piped. In other cases, growers take measures to retard the ripening action of natural ethylene. Stored apples are often flushed with CO_2, which inhibits the action of ethylene. In this way, apples picked in autumn can be stored for sale the following summer.

Why can one bad peach spoil a whole bowlful?

Leaf Drop

The loss of leaves in autumn is affected by ethylene. Leaf drop is triggered by environmental stimuli, including the shortening days of autumn and cooler temperatures. These stimuli cause a change in the balance of ethylene and auxins that weakens the cell walls in a layer of cells at the base of the leaf stalk. The weight of the leaf, often assisted by wind, causes this layer to split, releasing the leaf. ☑

☑ CHECKPOINT

When you buy a bunch of bananas, you might bring them home in a plastic bag. If the bananas are too green to eat, would it be better to leave the bananas in the bag? Why?

Answer: It would be better to leave the bananas in the bag because this will cause ethylene gas to accumulate, which promotes ripening.

▼Figure 29.16 The effect of ethylene on the ripening of bananas. Two unripe bananas were stored for the same amount of time in bags. The banana on top was stored alone; the bottom banana was stored with an ethylene-releasing peach.



Cytokinins

Cytokinins are a group of closely related hormones that act as growth regulators. These regulators promote cell division, or cytokinesis. Cytokinins are produced in actively growing tissues, particularly in roots, embryos, and fruits.

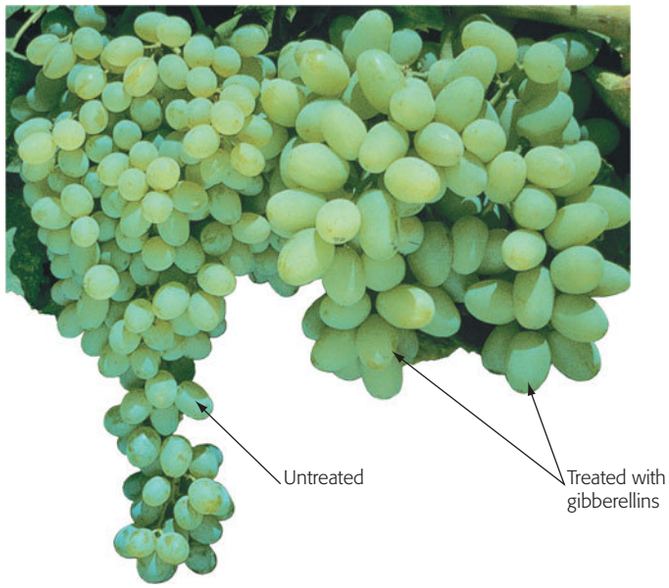
Cytokinins stimulate the growth of axillary buds, making a plant grow more branches and become bushy. Christmas tree growers sometimes use cytokinins to produce attractive branching. Cytokinins entering the shoot system from the roots counter the inhibitory effects of auxins coming down from the terminal buds. The complex growth patterns of most plants probably result from the relative concentrations of auxins and cytokinins.

Gibberellins

Gibberellins are another group of growth-regulating hormones. Roots and young leaves are major sites of gibberellin production. One of the main effects of gibberellins is to stimulate cell elongation and cell division in stems and leaves. This action generally enhances that of auxins. Also in combination with auxins, gibberellins can influence fruit development, and gibberellin-auxin sprays can make apples, currants, and eggplants develop without pollination and seed production. Gibberellins are used commercially to make seedless grapes grow larger and farther apart in a cluster, the benefits of which are evident in **Figure 29.17**.

Gibberellins are also important in seed germination in many plants. Many seeds that require special environmental conditions to germinate, such as exposure to light or cold, will germinate when sprayed with gibberellins. In nature, gibberellins in seeds are probably the link between environmental cues and the metabolic processes that reactivate growth of the embryo after a period of dormancy. For example, when water becomes available to a grass seed, it causes the embryo in the seed to release gibberellins, which promote germination by mobilizing nutrients stored in the seed.

Figure 29.17 The effect of gibberellins on grapes. The right cluster of grapes shows the effect of gibberellin treatment: larger grapes farther apart in the cluster.



Abscisic Acid

Unlike the growth-stimulating hormones we have studied so far, **abscisic acid** *slows* growth. One of the times in a plant's life when it is advantageous to suspend growth is at the onset of seed dormancy (inactivity of the seed). Seed dormancy is an evolutionary adaptation that ensures that a seed will germinate only when there are appropriate conditions of light, temperature, and moisture.

Many types of dormant seeds will germinate only when abscisic acid is removed or inactivated in some way. The seeds of some plants—such as the perennials rosemary and rhubarb—require prolonged exposure to cold during the winter to inactivate abscisic acid and trigger seed germination in the spring. The seeds of some desert plants remain dormant for years (even decades) until a sufficient downpour washes out the abscisic acid, allowing them to germinate when water is available for plant growth **(Figure 29.18)**. For many plants, the ratio of abscisic acid (which inhibits seed germination) to gibberellins (which promote seed germination) determines whether the seed will remain dormant or germinate. ☑

Figure 29.18 The effect of abscisic acid removal on seed dormancy. These wildflowers grew in the Organ Pipe Cactus National Monument, in Arizona, just after a hard rain washed abscisic acid out of the seeds, allowing them to germinate.



☑ CHECKPOINT

Which two hormones regulate seed dormancy and germination? What are their opposing effects?

Answer: Abscisic acid maintains seed dormancy; gibberellins promote germination.

Response to Stimuli

In this section, we'll consider how a plant responds to physical stimuli from the environment—including light, touch, and gravity.

Tropisms

Tropisms are directed growth responses that cause parts of a plant to grow toward or away from a stimulus (Figure 29.19). Phototropism, as you saw in Figure 29.13, is a particularly important example, but there are other directed growth responses. For example, **thigmotropism** is a response to touch, as when a pea tendril (which is actually a modified leaf) contacts a string or wire and coils around it for support. The tendril in the center photo in Figure 29.19 grew straight until it touched the support. Contact then stimulated the cells to grow at different rates on opposite sides of the tendril (slower in the contact area), making the tendril coil around the wire.

Gravitropism is the directional growth of a plant organ in response to gravity: Shoots grow upward and roots grow downward, regardless of the orientation of the seed. Auxins play an important role in gravitropism. The seedling shown on the right in Figure 29.19 responded to gravity by redistributing auxins to the lower side of its horizontally growing root. A high concentration of auxins inhibits the growth of root cells. As growth of the lower side of the root was slowed, cells on the upper side continued to elongate normally, and the root curved downward.

Why don't you have to worry about planting seeds upside down?

Photoperiod

In addition to providing energy for photosynthesis and directing growth, light helps regulate a plant's life cycle. Flowering, seed germination, and the onset and ending of dormancy are stages in plant development that usually occur at specific times of the year. The environmental stimulus that plants most often use to detect the time of year is called **photoperiod**, the relative lengths of day and night.

Plants whose flowering is triggered by photoperiod fall into two groups: long-night plants and short-night plants (Figure 29.20). (Historically, botanists erroneously referred to these plants as short- and long-day plants; we now know that it is night length, not day length, that affects a plant's flowering.) Long-night plants, such as chrysanthemum and poinsettia, generally flower in fall or winter, when nights lengthen. Short-night plants, such as lettuce, iris, and many grains, usually flower in spring or summer, when nights are briefer. Some plants, such as dandelions, are night-neutral; their flowering is unaffected by photoperiod. Florists apply knowledge of the photoperiod of particular plants to bring us flowers out of season. The blooming of chrysanthemums, for instance, can be stalled until spring by interrupting each long night with a flash of light, thus turning one long night into two short nights. ☑

☑ CHECKPOINT

1. A common houseplant called the "sensitive plant" (*Mimosa pudica*) has leaves that curl when touched. This is an example of what kind of growth response?
2. A particular long-night plant won't flower in the spring. You try to induce flowering by using a short, dark interruption to split a long-day period of spring into two short-day periods. What result do you predict?

Answers: **1.** *thigmotropism* **2.** *The plants still won't flower, because it is actually night length, not day length, that controls flowering.*

▼Figure 29.19 Tropisms.

TROPISMS (directed growth responses)

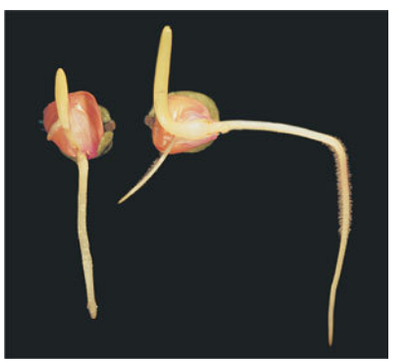
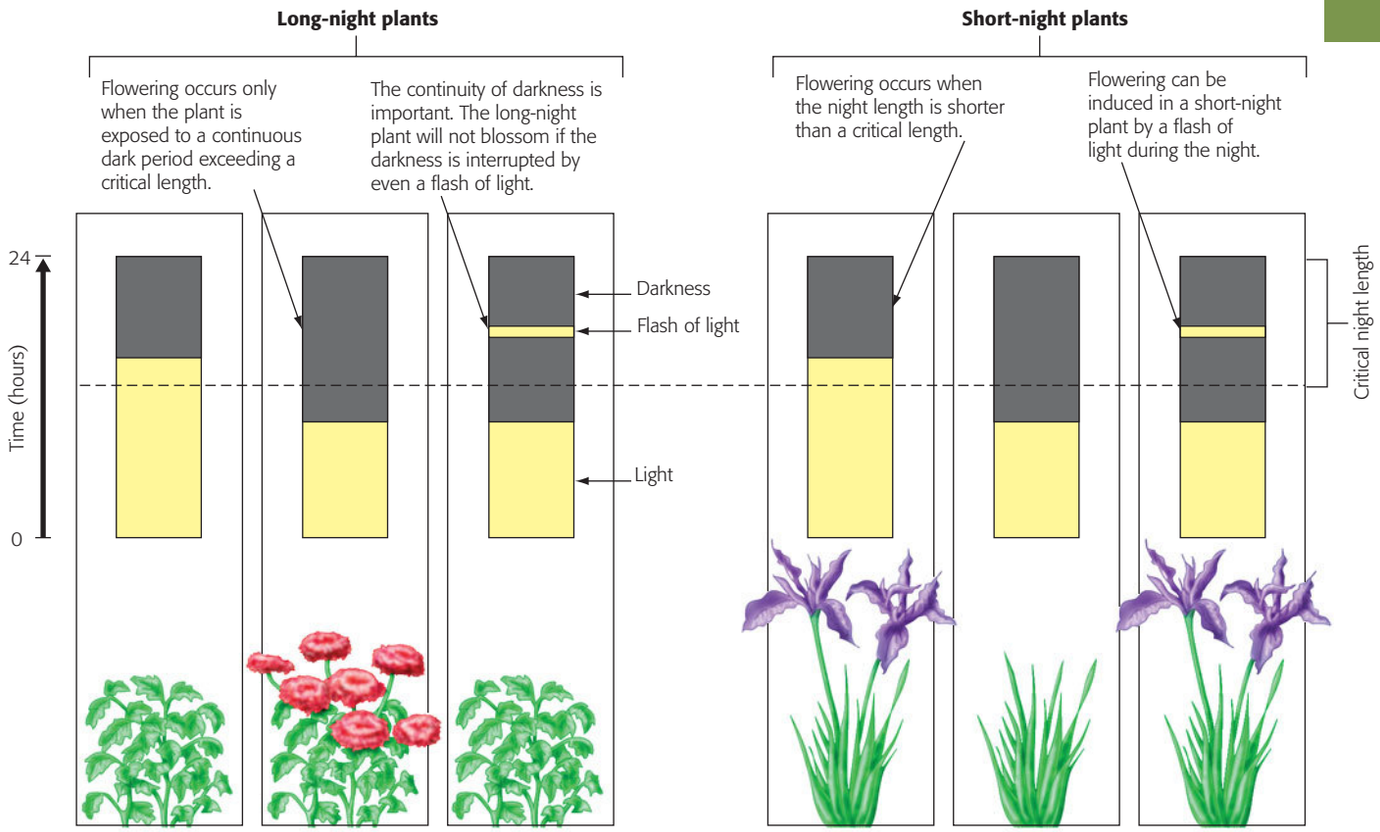
Phototropism	Thigmotropism	Gravitropism
		
These seedlings bending toward the light are young cilantro plants (a common herb).	Thigmotropism, growth in response to touch, allows vining plants to wrap around support structures. In this photo, the tendril of a pea plant coils around a wire fence.	These seedlings were both germinated in the dark. The one on the left was left alone. The one on the right was turned on its side two days after germination so that the shoot and root were horizontal. When this photo was taken, the shoot had turned back upward and the root had turned down.

Figure 29.20 Photoperiod and flowering. Photoperiod, the relative lengths of day and night, can trigger flowering.





The Interdependence of Organisms EVOLUTION CONNECTION

Plants, Mantises, and People

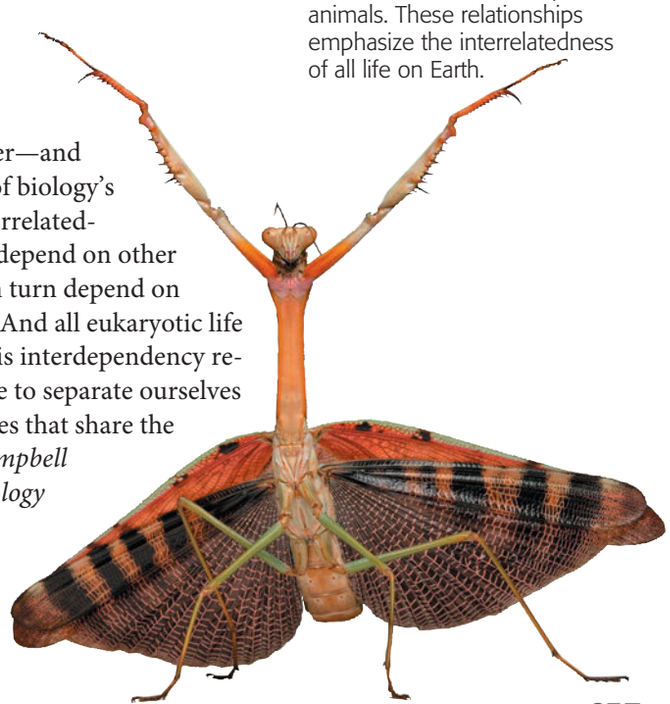
As you learned in the last chapter, most flowering plants depend on insects or other animals for pollination and seed dispersal. In this chapter, you saw that plants rely on organisms from two other kingdoms to help acquire nutrients: soil bacteria and the fungi of mycorrhizae. Indeed, the mycorrhizal connection may have altered the entire course of evolution by helping make possible the colonization of land. Today, nearly all land animals depend on plants (or animals that eat plants) for food.

Both the cover of this book and **Figure 29.21** show an African mega mantis (*Plistospilota guineensis*), a particularly striking member of the order Mantodea, a group of insects commonly called praying mantises. This species is found in western Africa, where its members occupy warm, damp, shrubby terrain. Like most mantises, the mega mantis is predatory: It lies in wait to ambush prey (such as flies, moths, crickets, and cockroaches) that strays near it, grasping its meal with its spiked legs.

In turn, mantises are themselves prey for spiders, frogs, birds, and even monkeys. When threatened, a mega mantis will sometimes spread its limbs and wings to appear bigger and more threatening.

Thus, we close this chapter—and this book—illustrating one of biology's overarching themes: the interrelatedness of organisms. Animals depend on other animals and plants, which in turn depend on animals, fungi, and protists. And all eukaryotic life depends on prokaryotes. This interdependency reminds us that it is impossible to separate ourselves from all of the living creatures that share the biosphere. We hope that *Campbell Essential Biology with Physiology* has given you a new appreciation of your place in the living world.

Figure 29.21 The interdependence of organisms. This African mega mantis (*Plistospilota guineensis*) depends on protists, plants, and animals for food and is itself eaten by other animals. These relationships emphasize the interrelatedness of all life on Earth.



Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

How Plants Acquire and Transport Nutrients

As a plant grows, its roots absorb water and minerals (inorganic ions) from the soil. Its leaves absorb CO_2 from the air.

Plant Nutrition

A plant must obtain from its surroundings usable sources of the chemical elements (nutrients) it requires.

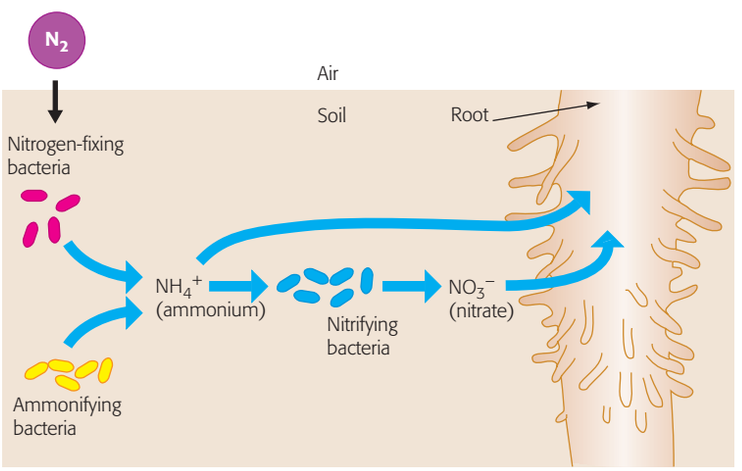
Nutrients	
Macronutrients	**Micronutrients**
• Needed in large amounts • Used to build organic molecules • Carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, calcium, potassium, magnesium	• Reusable, so needed in much smaller amounts • Iron, chlorine, copper, manganese, zinc, molybdenum, boron, nickel

From the Soil into the Roots

Root hairs greatly increase a root's absorbing surface. Water and solutes move through the root's epidermis and cortex, then into the xylem (water-conducting tissue) for transport upward. Relationships with other organisms help plants obtain nutrients. Many plants form mycorrhizae, mutually beneficial associations with fungi. A network of fungal threads increases a plant's absorption of nutrients, and the fungus receives nutrients from the plant.

The Role of Bacteria in Nitrogen Nutrition

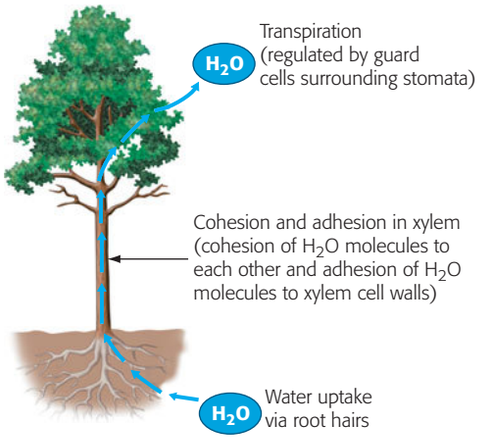
Most plants depend on bacteria to convert nitrogen to a form usable by the plant.



Legumes and certain other plants have nodules in their roots that house vesicles filled with nitrogen-fixing bacteria.

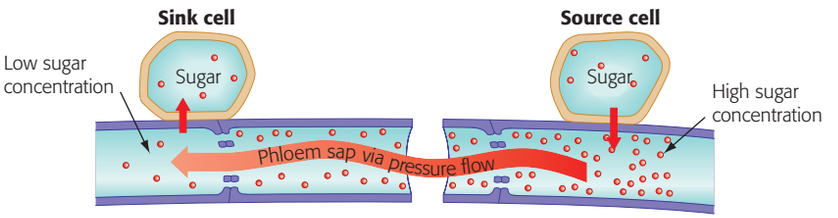
The Transport of Water

Water (and the solutes dissolved in it) moves upward from the roots within xylem tissue due to transpiration.



The Transport of Sugars

Phloem uses a pressure-flow mechanism to transport food molecules made by photosynthesis.



An increase in sugar concentration and water pressure at the sugar source and a decrease at the sugar sink cause phloem sap to flow from source to sink.

Plant Hormones

Hormones coordinate the internal activities of plants.

Auxins

Phototropism, directional growth in response to light, results from faster cell growth on the shaded side of the shoot than on the lighted side. This effect is regulated by auxins, a class of hormones. Plants produce auxins in the apical meristems at the tips of shoots. At different concentrations, auxins stimulate or inhibit the elongation of shoots and roots.

Ethylene

As a fruit ages, it gives off ethylene gas, which hastens ripening. A changing ratio of auxins to ethylene, triggered mainly by longer nights, causes the loss of leaves from certain trees.

Cytokinins

Cytokinins, produced by growing roots, embryos, and fruits, are hormones that promote cell division. The ratio of auxins to cytokinins helps coordinate the growth of roots and shoots.

Gibberellins

Gibberellins stimulate the elongation of stems and leaves and the development of fruits. Gibberellins released from embryos function in some of the early events of seed germination. Auxins and gibberellins are used in agriculture to produce seedless fruits.

Abscisic Acid

Abscisic acid inhibits the germination of seeds. The ratio of abscisic acid to gibberellins often determines whether a seed will remain dormant or germinate. Seeds of many plants remain dormant until their abscisic acid is inactivated or washed away.

Response to Stimuli

Tropisms

Tropisms are growth responses that make a plant grow toward or away from a stimulus. Important tropisms include phototropism, thigmotropism (a response to touch), and gravitropism (a response to gravity).

Photoperiod

Plants mark the seasons by measuring photoperiod, the relative lengths of night and day. The timing of flowering is one of the seasonal responses to photoperiod. Long-night plants flower when nights exceed a certain critical length; short-night plants flower when nights are shorter than a critical length.

SELF-QUIZ

1. Certain fungi cause diseases in plants. There are a variety of antifungal sprays that can be used to control this problem. Some gardeners constantly spray their plants with fungicides, even when no signs of disease are evident. How might this be disadvantageous to the plant?
2. Which of the following activities of soil bacteria does not contribute to creating usable nitrogen for plant use?
   a. the fixation of atmospheric nitrogen
   b. the conversion of ammonium to nitrate
   c. the assembly of amino acids into proteins
   d. the generation of ammonium from proteins in dead leaves
3. Plants transport two types of sap. _____ sap, a solution of mostly water and sucrose, is transported from sites of sugar production to other parts of the plant. _____ sap, a solution of mostly water and inorganic ions, is transported from the roots to the rest of the plant body.
4. Contrast cohesion and adhesion, and describe the role of each in the ascent of xylem sap.
5. Auxins cause a shoot to bend toward light by
   a. causing cells to shrink on the dark side of the shoot.
   b. stimulating growth on the dark side of the shoot.
   c. causing cells to shrink on the lighted side of the shoot.
   d. stimulating growth on the lighted side of the shoot.
6. The status of axillary buds—dormant or growing—depends on the relative concentrations of _____ moving down from the shoot tip and _____ moving up from the roots.
7. Why do many plants become bushier if you pinch off their terminal buds?
8. Match each of the following hormones to its primary role in a plant.

a. auxins	1. at different concentrations, stimulate or inhibit the elongation of shoots and roots
b. ethylene	2. produced by roots, promote cell division
c. cytokinins	3. inhibits seed germination
d. gibberellins	4. hastens fruit ripening
e. abscisic acid	5. promote fruit development

9. Match each of the following terms to its meaning.

a. gravitropism	1. growth response to light
b. photoperiod	2. growth response to touch
c. phototropism	3. relative lengths of night and day
d. thigmotropism	4. growth response to gravity

10. Jon just started a new job as night watchman at a plant nursery. His boss told him to stay out of a room where chrysanthemums (which are long-night plants) were about to flower. Around midnight, looking for the rest room, Jon accidentally opened the door to the chrysanthemum room and turned on the lights for a moment. How might this affect the chrysanthemums?

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

11. In some situations, the application of nitrogen fertilizer to crops has to be increased each year because the fertilizer decreases the rate of nitrogen fixation in the soil. Propose a hypothesis to explain this phenomenon. Describe a test for your hypothesis. What results would you expect from your test?

BIOLOGY AND SOCIETY

12. Agriculture is by far the biggest user of water in arid western states, including Colorado, Arizona, and California. The populations of these states are growing, and there is an ongoing conflict between cities and farm regions over water. To ensure water supplies for urban growth, cities are purchasing water rights from farmers. This is often the least expensive way for a city to obtain more water, and some farmers can make more money selling water than growing crops. Discuss the possible consequences of this trend. Is this the best way to allocate water for all concerned? Why or why not?
13. Imagine the following scenario: A plant scientist has developed a synthetic chemical that mimics the effects of a plant hormone. The chemical can be sprayed on apples before harvest to prevent flaking of the natural wax that is formed on the skin. This makes the apples shinier and gives them a deeper color. What kinds of questions do you think should be answered before farmers start using this chemical on apples? How might the scientist go about finding answers to these questions?

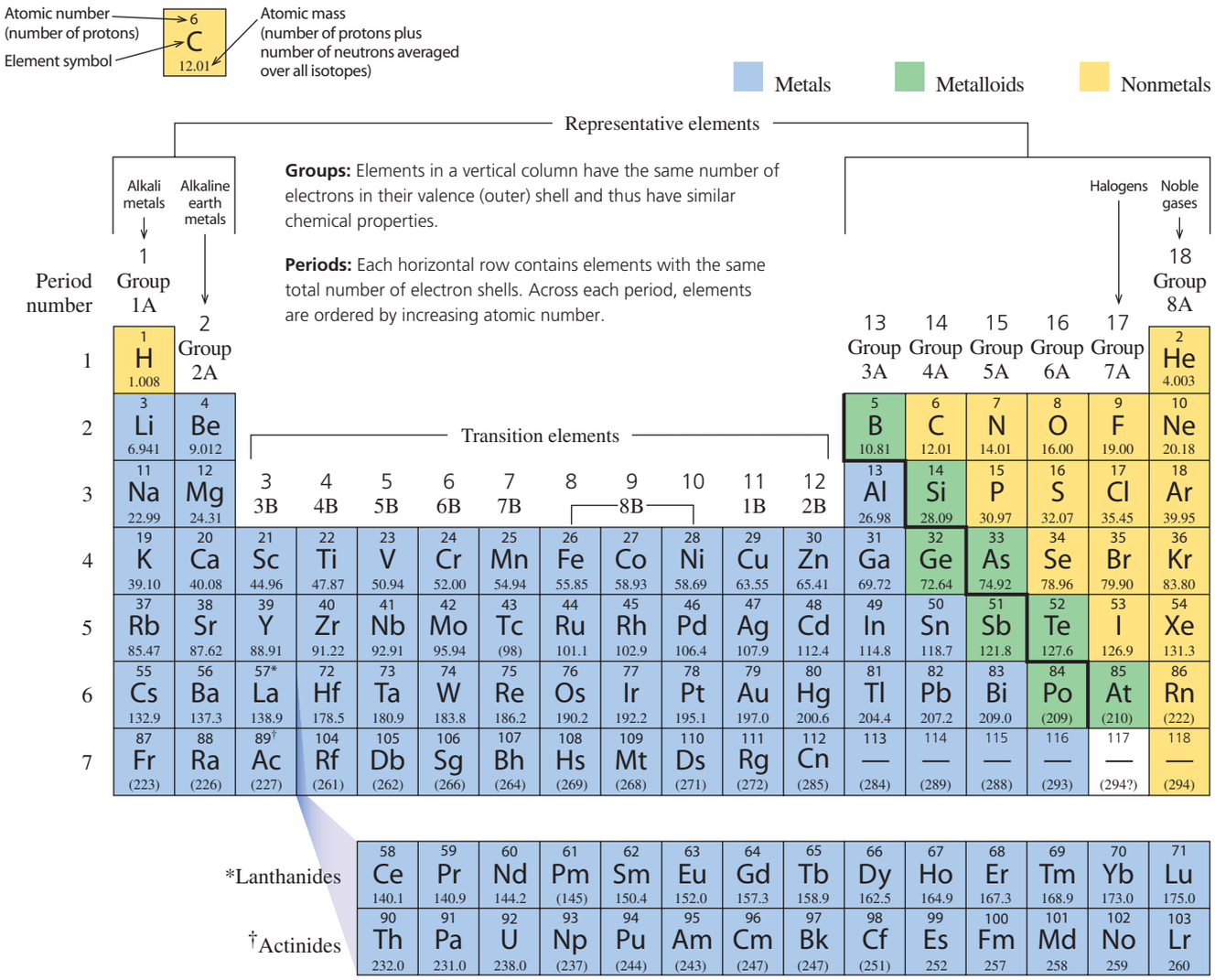
This page intentionally left blank

Appendix A Metric Conversion Table

MEASUREMENT	UNIT AND ABBREVIATION	METRIC EQUIVALENT	APPROXIMATE METRIC-TO-ENGLISH CONVERSION FACTOR	APPROXIMATE ENGLISH-TO-METRIC CONVERSION FACTOR
Length	1 kilometer (km) 1 meter (m) 1 centimeter (cm) 1 millimeter (mm) 1 micrometer (μm) 1 nanometer (nm) 1 angstrom (Å)	= 1,000 (10^3) meters = 100 (10^2) centimeters = 1,000 millimeters = 0.01(10^{-2}) meter = 0.001 (10^{-3}) meter = 10^{-6} meter (10^{-3} mm) = 10^{-9} meter (10^{-3} μm) = 10^{-10} meter (10^{-4} μm)	1 km = 0.6 mile 1 m = 1.1 yards 1 m = 3.3 feet 1 m = 39.4 inches 1 cm = 0.4 inch 1 mm = 0.04 inch	1 mile = 1.6 km 1 yard = 0.9 m 1 foot = 0.3 m 1 foot = 30.5 cm 1 inch = 2.5 cm
Area	1 hectare (ha) 1 square meter (m^2) 1 square centimeter (cm^2)	= 10,000 square meters = 10,000 square centimeters = 100 square millimeters	1 ha = 2.5 acres 1 m^2 = 1.2 square yards 1 m^2 = 10.8 square feet 1 cm^2 = 0.16 square inch	1 acre = 0.4 ha 1 square yard = 0.8 m^2 1 square foot = 0.09 m^2 1 square inch = 6.5 cm^2
Mass	1 metric ton (t) 1 kilogram (kg) 1 gram (g) 1 milligram (mg) 1 microgram (μg)	= 1,000 kilograms = 1,000 grams = 1,000 milligrams = 10^{-3} gram = 10^{-6} gram	1 t = 1.1 tons 1 kg = 2.2 pounds 1 g = 0.04 ounce 1 g = 15.4 grains 1 mg = 0.02 grain	1 ton = 0.91 t 1 pound = 0.45 kg 1 ounce = 28.35 g
Volume *(solids)*	1 cubic meter (m^3) 1 cubic centimeter (cm^3 or cc) 1 cubic millimeter (mm^3)	= 1,000,000 cubic centimeters = 10^{-6} cubic meter = 10^{-9} cubic meter (10^{-3} cubic centimeter)	1 m^3 = 1.3 cubic yards 1 m^3 = 35.3 cubic feet 1 cm^3 = 0.06 cubic inch	1 cubic yard = 0.8 m^3 1 cubic foot = 0.03 m^3 1 cubic inch = 16.4 cm^3
Volume *(liquids and gases)*	1 kiloliter (kL or kl) 1 liter (L) 1 milliliter (mL or ml) 1 microliter (μl or μL)	= 1,000 liters = 1,000 millimeters = 10^{-3} liter = 1 cubic centimeter = 10^{-6} liter (10^{-3} milliliters)	1 kL = 264.2 gallons 1 L = 0.26 gallon 1 L = 1.06 quarts 1 mL = 0.03 fluid ounce 1 mL = approx. ¼ teaspoon 1 mL = approx. 15–16 drops	1 gallon = 3.79 L 1 quart = 0.95 L 1 quart = 946 mL 1 pint = 473 mL 1 fluid ounce = 29.6 mL 1 teaspoon = approx. 5 mL
Time	1 second (s) 1 millisecond (ms)	= $\frac{1}{60}$ minute = 10^{-3} second		
Temperature	Degrees Celsius (°C)		°F = $\frac{9}{5}$°C + 32	°C = $\frac{5}{9}$(°F − 32)

This page intentionally left blank

Appendix B The Periodic Table



Period number	1 Group 1A	2 Group 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 Group 3A	14 Group 4A	15 Group 5A	16 Group 6A	17 Group 7A	18 Group 8A
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57* La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89† Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (269)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Cn (285)	113 — (284)	114 — (289)	115 — (288)	116 — (293)	117 — (294?)	118 — (294)

*Lanthanides	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
†Actinides	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 260

NAME (SYMBOL)	ATOMIC NUMBER	NAME (SYMBOL)	ATOMIC NUMBER	NAME (SYMBOL)	ATOMIC NUMBER	NAME (SYMBOL)	ATOMIC NUMBER	NAME (SYMBOL)	ATOMIC NUMBER
Actinium (Ac)	89	Copernicium (Cn)	112	Iridium (Ir)	77	Palladium (Pd)	46	Sodium (Na)	11
Aluminum (Al)	13	Copper (Cu)	29	Iron (Fe)	26	Phosphorus (P)	15	Strontium (Sr)	38
Americium (Am)	95	Curium (Cm)	96	Krypton (Kr)	36	Platinum (Pt)	78	Sulfur (S)	16
Antimony (Sb)	51	Darmstadtium (Ds)	110	Lanthanum (La)	57	Plutonium (Pu)	94	Tantalum (Ta)	73
Argon (Ar)	18	Dubnium (Db)	105	Lawrencium (Lr)	103	Polonium (Po)	84	Technetium (Tc)	43
Arsenic (As)	33	Dysprosium (Dy)	66	Lead (Pb)	82	Potassium (K)	19	Tellurium (Te)	52
Astatine (At)	85	Einsteinium (Es)	99	Lithium (Li)	3	Praseodymium (Pr)	59	Terbium (Tb)	65
Barium (Ba)	56	Erbium (Er)	68	Lutetium (Lu)	71	Promethium (Pm)	61	Thallium (Tl)	81
Berkelium (Bk)	97	Europium (Eu)	63	Magnesium (Mg)	12	Protactinium (Pa)	91	Thorium (Th)	90
Beryllium (Be)	4	Fermium (Fm)	100	Manganese (Mn)	25	Radium (Ra)	88	Thulium (Tm)	69
Bismuth (Bi)	83	Fluorine (F)	9	Meitnerium (Mt)	109	Radon (Rn)	86	Tin (Sn)	50
Bohrium (Bh)	107	Francium (Fr)	87	Mendelevium (Md)	101	Rhenium (Re)	75	Titanium (Ti)	22
Boron (B)	5	Gadolinium (Gd)	64	Mercury (Hg)	80	Rhodium (Rh)	45	Tungsten (W)	74
Bromine (Br)	35	Gallium (Ga)	31	Molybdenum (Mo)	42	Roentgenium (Rg)	111	Uranium (U)	92
Cadmium (Cd)	48	Germanium (Ge)	32	Neodymium (Nd)	60	Rubidium (Rb)	37	Vanadium (V)	23
Calcium (Ca)	20	Gold (Au)	79	Neon (Ne)	10	Ruthenium (Ru)	44	Xenon (Xe)	54
Californium (Cf)	98	Hafnium (Hf)	72	Neptunium (Np)	93	Rutherfordium (Rf)	104	Ytterbium (Yb)	70
Carbon (C)	6	Hassium (Hs)	108	Nickel (Ni)	28	Samarium (Sm)	62	Yttrium (Y)	39
Cerium (Ce)	58	Helium (He)	2	Niobium (Nb)	41	Scandium (Sc)	21	Zinc (Zn)	30
Cesium (Cs)	55	Holmium (Ho)	67	Nitrogen (N)	7	Seaborgium (Sg)	106	Zirconium (Zr)	40
Chlorine (Cl)	17	Hydrogen (H)	1	Nobelium (No)	102	Selenium (Se)	34		
Chromium (Cr)	24	Indium (In)	49	Osmium (Os)	76	Silicon (Si)	14		
Cobalt (Co)	27	Iodine (I)	53	Oxygen (O)	8	Silver (Ag)	47		

This page intentionally left blank

Appendix D Self-Quiz Answers

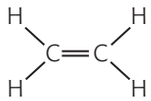
CHAPTER 1

1. b (some living organisms are single-celled)
2. atom, molecule, cell, tissue, organ, organism, population, ecosystem, biosphere; the cell
3. Photosynthesis cycles nutrients by converting the carbon in carbon dioxide to sugar, which is then consumed by other organisms. Additionally, the oxygen in water is released as oxygen gas. Photosynthesis contributes to energy flow by converting sunlight to chemical energy, which is then also consumed by other organisms, and by producing heat.
4. a4, b1, c3, d2.
5. On average, those individuals with heritable traits best suited to the local environment produce the greatest number of offspring that survive and reproduce. This increases the frequency of those traits in the population over time. The result is the accumulation of evolutionary adaptations.
6. Without a control group, you don't know if the experimental outcome is due to the variable you are trying to test or to some other variable.
7. d
8. c
9. Evolution
10. a3, b2, c1, d4

CHAPTER 2

1. electrons; neutrons; protons
2. Nitrogen-14 has an atomic number of 7 and a mass number of 14. The radioactive isotope, nitrogen-16, has an atomic number of 7 and a mass number of 16.
3. Organisms incorporate radioactive isotopes of an element into their molecules just as they do the nonradioactive isotopes, and researchers can detect the presence of the radioactive isotopes.
4. two
5. Each carbon atom has only three covalent bonds instead of the required four.
6. The positively charged hydrogen regions would repel each other.
7. d
8. a
9. The positive and negative poles cause adjacent water molecules to become attracted to each other, forming hydrogen bonds. The properties of water such as cohesion, temperature regulation, and water's ability to act as a solvent all arise from this atomic stickiness.
10. The cola is an aqueous solution, with water as the solvent, sugar as the main solute, and the CO_2 making the solution acidic.

CHAPTER 3

1. 

2. dehydration; water; hydrolysis
3. b
4. fatty acid; glycerol
5. b
6. c
7. d
8. Hydrophobic amino acids are most likely to be found within the interior of a protein, far from the watery environment.
9. a
10. starch (or glycogen or cellulose); nucleic acid
11. Both DNA and RNA are polynucleotides; both have the same phosphate group along the backbone; and both use A, C, and G bases. But DNA uses T while RNA uses U as a base; the sugar differs between them; and DNA is usually double-stranded, while RNA is usually single-stranded.
12. Structurally, a gene is a long stretch of DNA. Functionally, a gene contains the information needed to produce a protein.

CHAPTER 4

1. d
2. about 0.075 mm, which equals 75 μm
3. b
4. A membrane is fluid because its components are not locked into place. A membrane is mosaic because it contains a variety of embedded proteins.
5. endomembrane system
6. smooth ER; rough ER
7. rough ER, Golgi apparatus, plasma membrane
8. Both organelles use membranes to organize enzymes and both provide energy to the cell. But chloroplasts use pigments to capture energy from sunlight in photosynthesis, whereas mitochondria release energy from glucose using oxygen in cellular respiration. Chloroplasts are only in photosynthetic plants and protists, whereas mitochondria are in almost all eukaryotic cells.
9. a3, b1, c5, d2, e4
10. nucleus, nuclear pores, ribosomes, rough ER, Golgi apparatus
11. Both are motile appendages that extend from the surface of a cell and help in movement. Cells with flagella typically have one long flagellum that propels the cell in a whiplike motion; cilia are usually shorter, more numerous, and beat together.

CHAPTER 5

1. You convert the chemical energy from food to the kinetic energy of your upward climb. At the top of the stairs, some of the energy has been stored as potential energy because of your higher elevation. The rest has been converted to heat.
2. Energy; entropy
3. 10,000 g (or 10 kg); remember that 1 Calorie on a food label equals 1,000 calories of heat energy.
4. The three phosphate groups store chemical energy, a form of potential energy. The release of a phosphate group makes some of this potential energy available to cells to perform work.
5. Hydrolases are enzymes that participate in hydrolysis reactions, breaking down large molecules into the smaller molecules that make them up.
6. An inhibitor's binding to another site on the enzyme can cause the enzyme's active site to change shape.
7. b
8. a
9. *Hypertonic* and *hypotonic* are relative terms. A solution that is hypertonic to tap water could be hypotonic to seawater. In using these terms, you must provide a comparison, as in "The solution is hypertonic to the cell's cytoplasm."
10. Passive transport moves atoms or molecules along their concentration gradient (from higher to lower concentration), while active transport moves them against their concentration gradient.
11. b
12. signal transduction pathway

CHAPTER 6

1. d
2. Plants produce organic molecules by photosynthesis. Consumers must acquire organic material by consuming it rather than making it.
3. In breathing, your lungs exchange CO_2 and O_2 between your body and the atmosphere. In cellular respiration, your cells consume the O_2 in extracting energy from food and release CO_2 as a waste product.
4. the electron transport chain
5. glucose; NAD^+
6. O_2
7. The majority of the energy provided by cellular respiration is generated during the electron transport chain. Shutting down that pathway will deprive cells of energy very quickly.
8. b
9. Glycolysis
10. b
11. Because fermentation supplies only 2 ATP per glucose molecule compared with about 32 from cellular respiration, the yeast will have to consume 19 times as much glucose to produce the same amount of ATP.

CHAPTER 7

1. thylakoids; stroma
2. The Calvin cycle, which consumes the NADPH and ATP, occurs in the stroma.
3. inputs: a, d, e; outputs: b, c
4. Green light is reflected by chlorophyll, not absorbed, and therefore cannot drive photosynthesis.
5. H_2O
6. c
7. The reactions of the Calvin cycle require the outputs of the light reactions (ATP and NADPH).
8. In hot, dry environments, most plants close their stomata, which saves water but decreases the amount of CO_2 available inside the leaves.

9. C_4 and CAM plants can close their stomata and save water without shutting down photosynthesis.
10. c

CHAPTER 8

1. c
2. They have identical genes (DNA).
3. They are in the form of very long, thin strands.
4. b
5. prophase and telophase
6. a. 1,1; b. 1, 2; c. 2, 4; d. $2n$, n; e. individually, by homologous pair; f. identical, unique; g. repair, growth, asexual reproduction; gamete formation
7. c
8. 39
9. Prophase II or metaphase II; it cannot be during meiosis I because then you would see an even number of chromosomes; it cannot be during a later stage of meiosis II because then you would see the sister chromatids separated.
10. benign; malignant
11. 16 ($2n = 8$, so $n = 4$ and $2^n = 2^4 = 16$)
12. Nondisjunction would create just as many gametes with an extra copy of chromosome 3 or 16, but extra copies of chromosome 3 or 16 are probably fatal.

CHAPTER 9

1. genotype; phenotype
2. Statement **a.** is the law of independent assortment; statement **b.** is the law of segregation.
3. c
4. c
5. d
6. d
7. d
8. $\frac{1}{4}$ ($\frac{1}{2}$ chance the child will be male times $\frac{1}{2}$ chance that he will inherit the X carrying the disease allele)
9. The two parental-type gametes, *WS* and *ws*, are produced through meiosis. The process of recombination (due to crossing over) can produce two kinds of recombinant gametes, *Ws* and *wS*.
10. Height appears to result from polygenic inheritance, like human skin color. See Figure 9.22.
11. The brown allele appears to be dominant, the white allele recessive. The brown parent appears to be homozygous dominant, *BB*, and the white mouse is homozygous recessive, *bb*. The F_1 mice are all heterozygous, *Bb*. If two of the F_1 mice are mated, $\frac{3}{4}$ of the F_2 mice will be brown.
12. The best way to find out whether a brown F_2 mouse is homozygous dominant or heterozygous is to do a testcross: Mate the brown mouse with a white mouse. If the brown mouse is homozygous, all the offspring will be brown. If the brown mouse is heterozygous, you would expect half the offspring to be brown and half to be white.
13. Freckles are dominant, so Tim and Jan must both be heterozygous. There is a $\frac{3}{4}$ chance that they will produce a child with freckles, a $\frac{1}{4}$ chance that they will produce a child without freckles. The probability that the next two children will have freckles is $\frac{3}{4} \times \frac{3}{4} = \frac{9}{16}$.
14. According to the odds, half their children will be heterozygous and have elevated cholesterol levels. There is a $\frac{1}{4}$ chance that their next child will be homozygous, *hh,* and have an extremely high cholesterol level, like Katerina.
15. The bristle-shape alleles are sex-linked, carried on the X chromosome. Normal bristles is dominant *(F)* and forked is recessive *(f)*. The genotype of the female parent is X^fX^f. The genotype of the male parent is X^FY. Their female offspring are X^FX^f; their male offspring are X^fY.
16. The mother is a heterozygous carrier, and the father is normal. See Figure 9.32 for a pedigree. $\frac{1}{4}$ of their children will be boys suffering from hemophilia; $\frac{1}{4}$ will be female carriers.
17. For a woman to be colorblind, she must inherit X chromosomes bearing the colorblindness allele from both parents. Her father has only one X chromosome, which he passes on to all his daughters, so he must be colorblind. A male only needs to inherit the colorblindness allele from a carrier mother; both his parents are usually phenotypically normal.

CHAPTER 10

1. polynucleotides; nucleotides; sugar (deoxyribose); phosphate; nitrogenous base
2. b
3. Each daughter DNA molecule will have half the radioactivity of the parent molecule, since one polynucleotide from the original parental DNA molecule winds up in each daughter DNA molecule.
4. CAU; GUA; histidine (His)
5. A gene is the polynucleotide sequence with information for making one polypeptide. Each codon—a triplet of bases in DNA or RNA—codes for one amino acid. Transcription occurs when RNA polymerase produces mRNA using one strand of DNA as a template. A ribosome is the site of translation, or polypeptide synthesis, and tRNA molecules serve as interpreters of the genetic code. Each tRNA molecule has an amino acid attached at one end and a three-base anticodon at the other end. Beginning at the start codon, mRNA moves relative to the ribosome a codon at a time. A tRNA with a complementary anticodon pairs with each codon, adding its amino acid to the polypeptide chain. The amino acids are linked by peptide bonds. Translation stops at a stop codon, and the finished polypeptide is released. The polypeptide folds to form a functional protein, sometimes in combination with other polypeptides.
6. a3, b3, c1, d2, e2 and 3
7. d
8. d
9. The genetic material of these viruses is RNA, which is replicated inside the infected cell by special enzymes encoded by the virus. The viral genome (or its complement) serves as mRNA for the synthesis of viral proteins.
10. reverse transcriptase
11. The process of reverse transcription occurs only in infections by RNA-containing retroviruses like HIV. Cells do not require reverse transcriptase (their RNA molecules do not undergo reverse transcription), so reverse transcriptase can be knocked out without harming the human host.

CHAPTER 11

1. c
2. operon
3. b
4. a
5. DNA polymerase and other proteins required for transcription do not have access to tightly packed DNA.
6. the ability of these cells to produce entire organisms through cloning
7. nuclear transplantation
8. which genes are active in a particular sample of cells
9. b
10. embryonic tissue (ES cells), umbilical cord blood, and bone marrow (adult stem cells)
11. Proto-oncogenes are normal genes involved in the control of the cell cycle. Mutation or viruses can cause them to be converted to oncogenes, or cancer-causing genes. Proto-oncogenes are necessary for normal control of cell division.
12. Master control genes, called homeotic genes, regulate many other genes during development.

CHAPTER 12

1. c, d, b, a
2. because it does not contain introns
3. vector
4. Such an enzyme creates DNA fragments with "sticky ends," single-stranded regions whose unpaired bases can hydrogen-bond to the complementary sticky ends of other fragments created by the same enzyme.
5. PCR
6. Different people tend to have different numbers of repeats at each STR site. DNA fragments prepared from the STR sites of different people will thus have different lengths, causing them to migrate to different locations on a gel.
7. a
8. b
9. Chop the genome into fragments using restriction enzymes, clone and sequence each fragment, and reassemble the short sequences into

a continuous sequence for every chromosome.
10. c, b, a, d

CHAPTER 13

1. c
2. Lyell and other geologists presented evidence for the gradual change of geologic features over millions of years. Darwin applied this idea to suggest that species evolve through the slow accumulation of small changes over long periods of time.
3. *Bb*: 0.42; *BB*: 0.49; *bb*: 0.09
4. The fitness of an individual (or of a particular genotype) is measured by the relative number of alleles that it contributes to the gene pool of the next generation compared with the contribution of others. Thus the number of fertile offspring produced determines an individual's fitness.
5. e
6. c
7. Both effects result in populations small enough for significant sampling error in the gene pool for the first few generations. A bottleneck event reduces the size of an existing population in a given location. The founder effect occurs when a new, small population colonizes a new territory.
8. stabilizing selection
9. b, c, d
10. the prevalence of malaria

CHAPTER 14

1. Microevolution is a change in the gene pool of a population, often associated with adaptation. Speciation is an evolutionary process in which one species splits into two or more species. Macroevolution is evolutionary change above the species level, including the origin of evolutionary novelty and new taxonomic groups and the impact of mass extinctions on the diversity of life and its subsequent recovery. Macroevolution is marked by major changes in the history of life, including the origin of new species, and these changes are often noticeable enough to be evident in the fossil record.
2. b
3. prezygotic: a, b, c, e; postzygotic: d
4. because a small gene pool is more likely to be changed substantially by genetic drift and natural selection
5. exaptations
6. d
7. d
8. species, genus, family, order, class, phylum, kingdom, domain
9. 2.6
10. Archaea and Bacteria

CHAPTER 15

1. g, d, f, c, b, a, e
2. d, c, a, b, e
3. DNA polymerase is a protein, which must be transcribed from a gene. But a DNA gene requires DNA polymerase to be replicated. This creates a paradox about which came first—DNA or protein. But RNA can act as both an information storage molecule and an enzyme, suggesting that dual-role RNA may have preceded both DNA and proteins.
4. Exotoxins are poisons secreted by pathogenic bacteria; endotoxins are components of the outer membrane of pathogenic bacteria.
5. Autotrophs make their own organic compounds from CO_2, while heterotrophs must obtain at least one type of organic compound from another organism.
6. They can form endospores.
7. Both you and a mushroom are chemoheterotrophs.
8. because the first eukaryotes were protists, and these ancient protists were ancestral to all other eukaryotes, including plants, fungi, animals, and modern protists
9. c
10. b

CHAPTER 16

1. cuticle
2. flowers
3. a. sporophyte b. cones; angiosperms c. fruit
4. b
5. b
6. a fern
7. Because the plants do not lose their leaves during autumn and winter, the leaves are already fully developed for photosynthesis when the short growing season begins in spring.
8. vascular plant
9. a
10. a ripened ovary of a flower that protects and aids in the dispersal of seeds contained in the fruit
11. algae; fungi
12. A fungus digests its food externally by secreting digestive juices into the food and then absorbing the small nutrients that result from digestion. In contrast, humans and most other animals ingest relatively large pieces of food and digest the food within their bodies.

CHAPTER 17

1. c
2. coelom; pseudocoelom
3. arthropod
4. amphibians
5. b
6. Chordata; notochord; cartilage disks between your vertebrae
7. bipedalism
8. a
9. *Australopithecus* species, *Homo habilis, Homo erectus, Homo sapiens*
10. a4, b5, c1, d2, e3

CHAPTER 18

1. organismal ecology, population ecology, community ecology, ecosystem ecology
2. light, water temperature, chemicals added
3. physiological; behavioral
4. d
5. a. desert; b. grassland; c. tropical rain forest; d. temperate broadleaf forest; e. coniferous forest; f. tundra
6. chaparral
7. permafrost, very cold winters, and high winds
8. agriculture
9. Carbon dioxide and other gases in the atmosphere absorb heat energy radiating from Earth and reflect it back toward Earth. This is called the greenhouse effect. As the carbon dioxide concentration in the atmosphere increases, more heat is retained, causing global warming.
10. c
11. populations of organisms that have high genetic variability and short life spans

CHAPTER 19

1. the number of people and the land area in which they live
2. III; I
3. O; O; E; O; E
4. a. The *x*-axis is time; the *y*-axis is the number of individuals; the red curve represents exponential growth; the blue curve represents logistic growth.
   b. carrying capacity
   c. In exponential growth, the population growth rate continues to increase as long as the population size increases. In logistic growth, the population grows fastest when it is about ½ the carrying capacity.
   d. exponential growth curve, though the worldwide growth rate is slowing
5. d
6. opportunistic
7. c
8. The large population segment, the baby boomers, are currently in the workforce and are in their peak earning years.
9. d

CHAPTER 20

1. habitat destruction
2. d
3. c
4. a2, b5, c5, d3 or d4, e1
5. because the pesticides become concentrated in their prey
6. succession
7. Only 10% of the energy trapped by photosynthesis is turned into biomass by the plant, and only 10% of that energy is turned into the meat of a grazing animal. Therefore, eating grain-fed beef obtains only about 1% of the energy captured by photosynthesis.
8. Many nutrients come from the soil, but carbon comes from the air.
9. landscape
10. b

CHAPTER 21

1. atom, molecule, organelle, cell, tissue, organ, organ system, organism
2. A very thin or flat organism may have all of its body cells in contact with the environment and therefore would not need a circulatory system. In contrast, a thicker organism will require a circulatory system to transport substances to all body cells.
3. c

4. interstitial fluid
5. positive; negative
6. Endotherms get most of their body heat from metabolic processes, whereas ectotherms get most of their body heat from the environment.
7. osmoregulator; osmoconformer
8. d
9. b
10. Most of the water is reabsorbed into the blood; the rest is excreted in the urine.

CHAPTER 22

1. Large food items could not be digested; it would be difficult to eliminate wastes; and it would be difficult to nourish the many cells that compose a large animal.
2. Yes, absorption is the uptake of nutrients into body cells. Without it, you would never gain any calories (or nutritional value) from your food.
3. Digestion; absorption
4. because peristalsis pushes the food along
5. proteins; pepsin
6. bacteria (specifically, *Helicobacter pylori*); by using antibiotics and bismuth
7. d
8. The antibiotics kill the bacteria that synthesize vitamin K in the colon.
9. b
10. because cellular respiration requires oxygen to break down food
11. Many plant proteins are incomplete, meaning that they lack certain essential amino acids. Animal products tend to have complete proteins that contain all the essential amino acids. Vegetarians must therefore eat a variety of plant products to receive all the essential amino acids.
12. a (Overdoses of fat-soluble vitamins can be dangerous because the body cannot rid itself of them quickly.)

CHAPTER 23

1. In an open circulatory system, vessels have open ends and the circulating fluid flows directly around the body cells. In a closed circulatory system, the circulating fluid stays within a closed system of vessels.
2. Arteries carry oxygen-rich blood to the body, but they carry oxygen-poor blood to the lungs. Veins carry oxygen-poor blood from the body to the heart, but they carry oxygen-rich blood from the lungs to the heart. Arteries are defined as vessels that carry blood away from the heart; veins carry blood to the heart.
3. a3, b1, c4, d2
4. Oxygen levels are reduced, as oxygen-depleted blood mixes with oxygen-rich blood.
5. anemia
6. a3, b4, c1, d2
7. fruits, vegetables, and whole grains; cholesterol, saturated fats, and trans fats
8. Gills (the respiratory organ of fishes) extend outward from the body into the surrounding environment, whereas lungs (the respiratory organ of humans) are internal.
9. alveoli
10. b
11. b

CHAPTER 24

1. antigens; antibodies
2. innate: a, b, d, e; adaptive: c, f, g
3. b
4. It takes several days for a clone of effector cells to be formed during the primary response. In a secondary response, memory cells can respond more quickly.
5. a4, b1, c6, d3, e2, f5
6. Swelling dilutes toxins, delivers more oxygen, promotes scabbing; pain changes behavior to discourage further damage; fever may inhibit bacterial growth.
7. HIV destroys helper T cells, thereby impairing both the cell-mediated and the humoral immune response.
8. B cells
9. In a person with lupus, the immune system makes antibodies against the person's own (self) molecules.
10. memory cells; clonal selection

CHAPTER 25

1. d
2. b
3. The first two cells could have membrane receptors for that hormone, but they might trigger different signal transduction pathways. The third cell could lack membrane receptors for that particular hormone.
4. b
5. Alcohol slows the release of antidiuretic hormone (ADH) from the pituitary. Decreased levels of ADH result in decreased levels of water reabsorption by the kidneys, increasing urine output.
6. The patient has hypothyroidism. The thyroid cannot produce its metabolism-regulating hormones without iodine.
7. d
8. c
9. At high levels, glucocorticoids suppress the immune system. Although this is good for relieving pain and inflammation, the immune system can no longer respond appropriately to threats such as infection. Additionally, glucocorticoids may mask pain, leading to behaviors that aggravate the injury.
10. androgens
11. a. endorphins b. human growth hormone (HGH) c. estrogens

CHAPTER 26

1. Asexual reproduction is favorable in a stable environment with many resources. Sexual reproduction may enhance success in a changing environment by producing genetically variable offspring.
2. the seminal vesicles and/or the prostate
3. a4, b6, c3, d1, e5, f2
4. b
5. Inhibiting FSH and LH after ovulation ensures that another egg will not be released during this cycle. Estrogen and progesterone inhibit FSH and LH.
6. They also help prevent the spread of sexually transmitted diseases.
7. a
8. c
9. The nerve cells may follow chemical trails to the muscle cells (induction).
10. oxytocin
11. in vitro fertilization; fertilization "in glass"

CHAPTER 27

1. cell body; dendrites; axon; synaptic terminal
2. It speeds up conduction of signals along an axon.
3. central nervous system; peripheral nervous system; brain; spinal cord
4. cerebrospinal fluid; meninges
5. activation of the sympathetic branch of the peripheral nervous system
6. The cerebral cortex deals with sensory information, while structures in the brainstem maintain vital functions. If a person suffers a severe head injury, the cerebral cortex may be damaged while the brainstem is still able to function, leaving the person unresponsive but alive.
7. An action potential (used by neurons) is an all-or-none situation; it doesn't vary in intensity. A receptor potential (used by sensory receptor cells) conveys information about the strength of the stimulus.
8. photoreceptor, chemoreceptor, mechanoreceptor, chemoreceptor
9. c (He can hear the tuning fork against his skull, so the cochlea, nerve, and brain are all functioning properly. Apparently, sounds are not being transmitted to the cochlea; therefore, the bones of the middle ear are the problem.)
10. axial; appendicular
11. d
12. a (Each neuron controls a smaller number of muscle fibers.)

CHAPTER 28

1. b, c, d, e
2. When most plants grow naturally, they exhibit apical dominance, which inhibits the outgrowth of the axillary buds. If your friend were to pinch back the terminal buds, there would be increased growth from the axillary buds. This would result in more branches and leaves, which would increase next year's yield.
3. ovary; ovule
4. a4, b2, c5, d6, e3, f1
5. sexual, because it generates genetic variation among the offspring, enhancing the potential for adaptation to a changing environment
6. a. fruit (ripened ovary); b. fruit; c. leaf; d. root; e. fruit
7. c
8. e
9. b; a
10. vascular cambium

CHAPTER 29

1. Excessive amounts of fungicides could destroy mycorrhizae,

symbiotic associations of fungi and plant root hairs. The fungal filaments provide lots of surface area for absorption of water and nutrients. Destroying the mycorrhizae could cause a water or nutrient deficiency in the plant.

2. c

3. Phloem; Xylem

4. Cohesion is the sticking together of identical molecules—water molecules in the case of xylem sap. Adhesion is the sticking together of different kinds of molecules, as in the adhesion of water to the cellulose of xylem walls. Cohesion enables transpiration to pull xylem sap up without the water in the vessels separating; adhesion helps to support the sap against the downward pull of gravity.

5. b

6. auxins; cytokinins

7. The terminal bud produces auxins, which counter the effects of cytokinins from the roots and inhibit the growth of axillary buds. If the terminal bud is removed, the cytokinins predominate, and branching occurs at the axillary buds.

8. a1; b4; c2; d5; e3

9. a4; b3; c1; d2

10. The room lights will inhibit flowering in the chrysanthemums.

This page intentionally left blank

Glossary

A

abiotic factor (*ā′bī-ot′-ik*)
A nonliving component of an ecosystem, such as air, water, light, minerals, or temperature.

abiotic reservoir
The part of an ecosystem where a chemical, such as carbon or nitrogen, accumulates or is stockpiled outside of living organisms.

ABO blood groups
Genetically determined classes of human blood that are based on the presence or absence of carbohydrates A and B on the surface of red blood cells. The ABO blood group phenotypes, also called blood types, are A, B, AB, and O.

abscisic acid (*ab-sis′-ik*)
A plant hormone that inhibits cell division and promotes dormancy. Abscisic acid interacts with gibberellins in regulating seed germination.

absorption
The uptake of small nutrient molecules by an organism's own body. In animals, absorption is the third main stage of food processing, following digestion; in fungi, it is acquisition of nutrients from the surrounding medium.

acclimation (*ak-li-mā-shun*)
Physiological adjustment that occurs gradually, though still reversibly, in response to an environmental change.

achondroplasia (*uh-kon′-druh-plā′-zhuh*)
A form of human dwarfism caused by a single dominant allele. The homozygous condition is lethal.

acid
A substance that increases the hydrogen ion (H^+) concentration in a solution.

action potential
A self-propagating change in the voltage across the plasma membrane of a neuron; a nerve signal.

activation energy
The amount of energy that reactants must absorb before a chemical reaction will start.

activator
A protein that switches on a gene or group of genes by binding to DNA.

active site
The part of an enzyme molecule where a substrate molecule attaches (by means of weak chemical bonds); typically, a pocket or groove on the enzyme's surface.

active transport
The movement of a substance across a biological membrane against its concentration gradient, aided by specific transport proteins and requiring the input of energy (often as ATP).

adaptive defense
An immune system defense that is found only in vertebrates and that must be activated by exposure to a specific invader.

adenine (A) (*ad′-uh-nēn*)
A double-ring nitrogenous base found in DNA and RNA.

adhesion
The attraction between different kinds of molecules.

adipose tissue
A type of connective tissue in which the cells contain fat.

ADP
Adenosine diphosphate (*a-den′-ō-sēn dī-fos′-fāt*)
A molecule composed of adenosine and two phosphate groups. The molecule ATP is made by combining a molecule of ADP with a third phosphate in an energy-consuming reaction.

adrenal cortex (*uh-drē′-nul*)
The outer portion of an adrenal gland, controlled by ACTH from the anterior pituitary; secretes hormones called glucocorticoids.

adrenal gland
One of a pair of endocrine glands, located atop each kidney in mammals, composed of an outer cortex and a central medulla.

adrenal medulla (*uh-drē′-nul muh-dul′-uh*)
The central portion of an adrenal gland, controlled by nerve signals; secretes the fight-or-flight hormones epinephrine and norepinephrine.

adult stem cell
A cell present in adult tissues that generates replacements for nondividing differentiated cells.

aerobic (*ār-ō′-bik*)
Containing or requiring molecular oxygen (O_2).

age structure
The relative number of individuals of each age in a population.

AIDS
Acquired immunodeficiency syndrome; the late stages of HIV infection, characterized by a reduced number of T cells; usually results in death caused by opportunistic infections.

alga (*al′-guh*)
(plural, **algae**) An informal term that describes a great variety of protists, most of which are unicellular or colonial photosynthetic autotrophs with chloroplasts. Heterotrophic and multicellular protists closely related to unicellular autotrophs are also regarded as algae.

alimentary canal (*al′-uh-men′-tuh-rē*)
A digestive tube running between a mouth and an anus; also called a digestive tract.

allele (*uh-lē′-ul*)
An alternative version of a gene.

allergen (*al′-er-jen*)
An otherwise harmless antigen that causes an allergic reaction.

allergy
An exaggerated sensitivity to an antigen. Symptoms are triggered by histamines released from mast cells.

allopatric speciation
The formation of a new species in populations that are geographically isolated from one another. *See also* sympatric speciation.

alternation of generations
A life cycle in which there is both a multicellular diploid form, the sporophyte, and a multicellular haploid form, the gametophyte; a characteristic of plants and multicellular green algae.

alternative RNA splicing
A type of regulation at the RNA-processing level in which different mRNA molecules are produced from the same primary transcript, depending on which RNA segments are treated as exons and which as introns.

alveolus (*al-vē′-oh-lus*)
(plural, **alveoli**) One of millions of tiny sacs within the vertebrate lungs where gas exchange occurs.

Alzheimer's disease
A form of mental deterioration, or dementia, characterized by confusion and memory loss.

amino acid (*uh-mēn′-ō*)
An organic molecule containing a carboxyl group, an amino group, a hydrogen atom, and a variable side group (also called a radical group or R group); serves as the monomer of proteins.

amniote
Member of a clade of tetrapods that has an amniotic egg containing specialized membranes that protect the embryo. Amniotes include mammals and reptiles (including birds).

amniotic egg (*am′-nē-ot′-ik*)
A shelled egg in which an embryo develops within a fluid-filled amniotic sac and is nourished by yolk. Produced by reptiles (including birds) and egg-laying mammals, it enables them to complete their life cycles on dry land.

amoeba (*uh-mē′-buh*)
A general term for a protozoan (animal-like protist) characterized by great structural flexibility and the presence of pseudopodia.

amphibian
Member of a class of vertebrate animals that includes frogs and salamanders.

anaerobic (*an′-ār-ō′-bik*)
Lacking or not requiring molecular oxygen (O_2).

analogy
The similarity between two species that is due to convergent evolution rather than to descent from a common ancestor with the same trait.

anaphase
The third stage of mitosis, beginning when sister chromatids separate from each other and ending when a complete set of daughter chromosomes has arrived at each of the two poles of the cell.

anatomy
The study of the structure of an organism and its parts.

androgen (*an′-drō-jen*)
A sex hormone secreted by the gonads that promotes the development and maintenance of the male reproductive system and male body features.

anemia (*uh-nē′-me-ah*)
A condition in which an abnormally low amount of hemoglobin or a low number of red blood cells results in the body cells not receiving enough oxygen.

angiosperm (*an′-jē-ō-sperm*)
A flowering plant, which forms seeds inside a protective chamber called an ovary.

animal
A eukaryotic, multicellular, heterotrophic organism that obtains nutrients by ingestion.

annelid (*an′-uh-lid*)
A segmented worm. Annelids include earthworms, polychaetes, and leeches.

annual
A plant that completes its life cycle in a single year or growing season.

anorexia nervosa
An eating disorder that results in self-starvation due to an intense fear of gaining weight, even when the person is underweight.

antagonistic hormones
Two hormones that have opposite effects.

anterior pituitary (*puh-tū′-uh-tār-ē*)
An endocrine gland, adjacent to the hypothalamus and the posterior pituitary, that synthesizes and secretes several hormones, including some that control the activity of other endocrine glands.

anther
A sac in which pollen grains develop, located at the tip of a flower's stamen.

anthropoid (*an′-thruh-poyd*)
Member of a primate group made up of the apes (gibbons, orangutans, gorillas, chimpanzees, and bonobos), monkeys, and humans.

antibody (*an′-tih-bod′-ē*)
A protein that is secreted by a B cell and attaches to a specific kind of antigen, helping counter its effects.

anticodon (*an′-tī-kō′-don*)
On a tRNA molecule, a specific sequence of three nucleotides that is complementary to a codon triplet on mRNA.

antigen (*an′-tuh-jen*)
Any molecule that elicits a response from a lymphocyte.

anus
The digestive system opening through which undigested materials are expelled.

aphotic zone (*ā-fō′-tik*)
The region of an aquatic ecosystem beneath the photic zone, where light levels are too low for photosynthesis to take place.

apical dominance (*ā′-pik-ul*)
In a plant, the hormonal inhibition of axillary buds by a terminal bud.

apical meristem (*ā′-pik-ul mer′-uh-stem*)
A meristem at the tip of a plant root or in the terminal or axillary bud of a shoot.

apicomplexan (*ap′-ē-kom-pleks′-un*)
A type of parasitic protozoan (animal-like protist). Some apicomplexans cause serious human disease.

appendicular skeleton
(*ap′-en-dik′-yū-ler*)
Components of the skeletal system that support the arms and legs of a land vertebrate; bones of the limbs, shoulders, and pelvis. *See also* axial skeleton.

appendix (*uh-pen′-dix*)
A small, finger-like extension near the union of the small and large intestines.

aqueous humor (*ā′-kwē-us hyū′-mer*)
A liquid in the space between the lens and cornea in the vertebrate eye that helps maintain the shape of the eye, supplies nutrients and oxygen to its tissues, and disposes of its wastes.

aqueous solution (*ā′-kwē-us*)
A solution in which water is the solvent.

arachnid
Member of a major arthropod group that includes spiders, scorpions, ticks, and mites.

Archaea (*ar-kē′-uh*)
One of two prokaryotic domains of life, the other being Bacteria.

archaean (*ar-kē′-uhn*)
(plural, **archaea**) An organism that is a member of the domain Archaea.

arteriole (*ar-tar′-ē-ōl*)
A small vessel that conveys blood between an artery and a capillary bed.

artery
A vessel that carries blood away from the heart to other parts of the body.

arthritis (*ar-thrī′-tis*)
A skeletal disorder characterized by inflamed joints and deterioration of the cartilage between bones.

arthropod (*ar′-thruh-pod*)
Member of the most diverse phylum in the animal kingdom; includes the horseshoe crab, arachnids (for example, spiders, ticks, scorpions, and mites), crustaceans (for example, crayfish, lobsters, crabs, and barnacles), millipedes, centipedes, and insects. Arthropods are characterized by a chitinous exoskeleton, molting, jointed appendages, and a body formed of distinct groups of segments.

asexual reproduction
The creation of genetically identical offspring by a single parent, without the participation of gametes (sperm and egg).

association areas
Areas of the cerbral cortex where different types of incoming sensory information are integrated.

astigmatism (*uh-stig′-muh-tizm*)
Blurred vision caused by a misshapen lens or cornea.

atherosclerosis (*ath′-uh-rō′-skluh-rō′-sis*)
A cardiovascular disease in which a buildup of fatty deposits called plaques develop on the inner walls of the arteries, narrowing the passageways through which blood can flow.

atom
The smallest unit of matter that retains the properties of an element.

atomic number
The number of protons in each atom of a particular element.

ATP Adenosine triphosphate (*a-den′-ō-sēn trī-fos′-fāt*)
A molecule composed of adenosine and three phosphate groups; the main energy source for cells. A molecule of ATP can be broken down to a molecule of ADP (adenosine diphosophate) and a free phosphate; this reaction releases energy that can be used for cellular work.

ATP synthase
A protein cluster, found in a cellular membrane (including the inner membrane of mitochondria, the thylakoid membrane of chloroplasts, and the plasma membrane of prokaryotes), that uses the energy of a hydrogen ion concentration gradient to make ATP from ADP. An ATP synthase provides a port through which hydrogen ions (H^+) diffuse.

atrium (*ā′-trē-um*)
(plural, **atria**) A heart chamber that receives blood from the body or lungs via veins.

auditory canal
The part of the outer ear that channels sound waves from the pinna, or outer body surface, to the eardrum.

autoimmune disease
An immunological disorder in which the immune system improperly attacks the body's own molecules.

autonomic nervous system
(*ot′-ō-nom′-ik*)
A component of the peripheral nervous system of vertebrates that regulates the internal environment. The autonomic nervous system is made up of the sympathetic and parasympathetic subdivisions. The autonomic nervous system is primarily under involuntary control.

autosome
A chromosome not directly involved in determining the sex of an organism; in mammals, for example, any chromosome other than X or Y.

autotroph (*ot′-ō-trōf*)
An organism that makes its own food from inorganic ingredients, thereby sustaining itself without eating other organisms or their molecules. Plants, algae, and photosynthetic bacteria are autotrophs.

auxin (*ok′-sin*)
Any of a group of plant hormones whose chief effect is to promote the growth and development of shoots.

AV (atrioventricular) node
A region of muscle tissue between the heart's right atrium and right ventricle. It generates electrical impulses that primarily cause the ventricles to contract.

axial skeleton (*ak′-sē-ul*)
Components of the skeletal system that support the central trunk of the body; the skull, backbone, and rib cage in a vertebrate. *See also* appendicular skeleton.

axillary bud (*ak′-sil-ār-ē*)
An embryonic shoot present in the angle formed by a leaf and stem.

axon (*ak′-son*)
A neuron fiber that extends from the cell body and conducts signals to another neuron or to an effector cell.

B

B cell
A type of lymphocyte that matures in the bone marrow and later produces antibodies; responsible for the humoral immune response. *See also* T cell.

bacillus (*buh-sil′-us*)
(plural, **bacilli**) A rod-shaped prokaryotic cell.

Bacteria
One of two prokaryotic domains of life, the other being Archaea.

bacteriophage (*bak-tēr′-ē-ō-fāj*)
A virus that infects bacteria; also called a phage.

bacterium
(plural, **bacteria**) An organism that is a member of the domain Bacteria.

ball-and-socket joint
A joint that allows rotation and movement in several planes. Examples in humans are the shoulder and hip joints.

bark
All the tissues external to the vascular cambium in a plant with secondary growth. Bark is made up of secondary phloem, cork cambium, and cork.

basal metabolic rate (BMR)
The number of kilocalories a resting animal requires to fuel its essential body processes for a given time.

base
A substance that decreases the hydrogen ion (H^+) concentration in a solution.

benign tumor
An abnormal mass of cells that remains at its original site in the body.

benthic realm
A seafloor or the bottom of a freshwater lake, pond, river, or stream. The benthic realm is occupied by communities of organisms known as benthos.

biennial
A plant that completes its life cycle in two years.

bilateral symmetry
An arrangement of body parts such that an organism can be divided equally by a single cut passing longitudinally through it. A bilaterally symmetric organism has mirror-image right and left sides.

bile
A solution of salts secreted by the liver that emulsifies fats and aids in their digestion.

binary fission
A means of asexual reproduction in which a parent organism, often a single cell, divides into two individuals of about equal size.

binomial
A two-part Latinized name of a species; for example, *Homo sapiens*.

biodiversity
The variety of living things; includes genetic diversity, species diversity, and ecosystem diversity.

biodiversity hot spot
A small geographic area that contains a large number of threatened or endangered species and an exceptional concentration of endemic species (those found nowhere else).

biofilm
A surface-coating cooperative colony of prokaryotes.

biogenesis
The principle that all life arises by the reproduction of preexisting life.

biogeochemical cycle
Any of the various chemical circuits occurring in an ecosystem, involving both biotic and abiotic components of the ecosystem.

biogeography
The study of the geographic distribution of species.

biological control
The intentional release of a natural enemy to attack a pest population.

biological magnification
The accumulation of persistent chemicals in the living tissues of consumers in food chains.

biological species concept
The definition of a species as a population or group of populations whose members have the potential in nature to interbreed and produce fertile offspring.

biology
The scientific study of life.

biomass
The amount, or mass, of living organic material in an ecosystem.

biome (*bī′-ōm*)
A major terrestrial or aquatic life zone, characterized by vegetation type in terrestrial biomes and the physical environment in aquatic biomes.

biophilia
The human desire to affiliate with other life in its many forms.

bioremediation
The use of living organisms to detoxify and restore polluted and degraded ecosystems.

biosphere
The global ecosystem; the entire portion of Earth inhabited by life; all of life and where it lives.

biotechnology
The manipulation of living organisms to perform useful tasks. Today, biotechnology often involves DNA technology.

biotic factor (*bī-ot′-ik*)
A living component of a biological community; any organism that is part of an individual's environment.

bipolar disorder
Depressive mental illness characterized by extreme mood swings; also called manic-depressive disorder.

bird
Member of a group of reptiles with feathers and adaptations for flight.

birth control pill
A chemical contraceptive that inhibits ovulation, retards follicular development, or alters a woman's cervical mucus to prevent sperm from entering the uterus.

bivalve
Member of a group of molluscs that includes clams, mussels, scallops, and oysters.

blade
The flattened portion of a typical leaf.

blastula (*blas′-tyū-luh*)
An embryonic stage that marks the end of cleavage during animal development; a hollow ball of cells in many species.

blood
A type of connective tissue with a fluid matrix called plasma in which blood cells are suspended.

blood pressure
The force that blood exerts against the walls of the blood vessels.

body cavity
A fluid-filled space separating the digestive tract from the outer body wall.

body mass index (BMI)
A ratio of weight to height used as a measure of obesity.

body segmentation
Subdivision of an animal's body into a series of repeated parts called segments.

bone
A type of connective tissue consisting of living cells held in a rigid matrix of collagen fibers embedded in calcium salts.

bony fish
A fish that has a stiff skeleton reinforced by calcium salts.

bottleneck effect
Genetic drift resulting from a drastic reduction in population size.

brain
The master control center of the central nervous system, which is involved in regulating and controlling body activity and interpreting information from the senses.

brainstem
A functional unit of the vertebrate brain, composed of the midbrain, medulla oblongata, and pons; serves mainly as a sensory filter, selecting which information reaches higher brain centers.

breathing
The ventilation of the lungs by alternate inhalation and exhalation, supplying a lung or gill with O_2-rich air or water and expelling CO_2-rich air or water.

bronchiole (*brong′-kē-ōl*)
A thin breathing tube that branches from a bronchus within a lung.

bronchus (*brong′-kus*)
(plural, **bronchi**) One of a pair of breathing tubes that branch from the trachea into the lungs.

bryophyte (*brī′-uh-fīt*)
A type of plant that lacks xylem and phloem; a nonvascular plant. Bryophytes include mosses and their close relatives.

budding
A means of asexual reproduction in which a new individual splits off after developing from an outgrowth of a parent.

buffer
A chemical substance that resists changes in pH by accepting hydrogen ions from or donating hydrogen ions to solutions.

bulimia
An eating disorder characterized by episodic binge eating followed by purging through induced vomiting, abuse of laxatives, or excessive exercise.

C

C_3 plant
A plant that used the Calvin cycle for the initial steps that incorporate CO_2 into organic material, forming a three-carbon compound as the first stable intermediate.

C_4 plant
A plant that prefaces the Calvin cycle with reactions that incorporate CO_2 into four-carbon compounds, the end product of which supplies CO_2 for the Calvin cycle.

calcitonin (*kal′-sih-tōn′-in*)
A peptide hormone, secreted by the thyroid gland, that lowers blood calcium level.

calorie
The amount of energy that raises the temperature of 1 g of water by 1°C.

Calvin cycle
The second of two stages of photosynthesis; a cyclic series of chemical reactions that occur in the stroma of a chloroplast, using the carbon in CO_2 and the ATP and NADPH produced by the light reactions to make the energy-rich sugar molecule G3P, which is later used to produce glucose.

CAM plant
A plant that uses the following adaptation for photosynthesis in arid conditions: Carbon dioxide entering open stomata during the night is converted to organic compounds, which release CO_2 for the Calvin cycle during the day, when stomata are closed.

cancer
A malignant growth or tumor caused by abnormal and uncontrolled cell division.

cap
Extra nucleotides added to the beginning of an RNA transcript in the nucleus of a eukaryotic cell.

capillary (*kap′-il-ar-ē*)
A microscopic blood vessel that conveys blood between an artery and a vein or between an arteriole and a venule; enables the exchange of nutrients and dissolved gases between the blood and interstitial fluid.

carbohydrate (*kar′-bō-hī′-drāt*)
A biological molecule consisting of a simple sugar (a monosaccharide), two monosaccharides joined into a double sugar (a disaccharide), or a chain of monosaccahrides (a polysaccharide).

carbon fixation
The initial incorporation of carbon from CO_2 into organic compounds by autotrophic organisms such as photosynthetic plants, algae, or bacteria.

carbon footprint
The amount of greenhouse gas emitted as a result of the actions of a person, nation, or other entity.

carcinogen (*kar-sin′-uh-jin*)
A cancer-causing agent, either high-energy radiation (such as X-rays or UV light) or a chemical.

cardiac cycle (*kar′-dē-ak*)
The alternating contractions and relaxations of the heart.

cardiac muscle
Striated muscle that forms the contractile tissue of the heart.

cardiovascular disease
(*kar′-dē-ō-vas′-kyū-ler*)
A set of diseases of the heart and blood vessels.

cardiovascular system
A closed circulatory system, found in vertebrates, with a heart and a branching network of arteries, capillaries, and veins.

carnivore
An animal that mainly eats other animals. *See also* herbivore; omnivore.

carpel (*kar′-pul*)
The egg-producing part of a flower, consisting of a stalk with an ovary at the base and a stigma, which traps pollen, at the tip.

carrier
An individual who is heterozygous for a recessively inherited disorder and who therefore does not show symptoms of that disorder.

carrying capacity
The maximum population size that a particular environment can sustain.

cartilage (*kar′-ti-lij*)
A type of connective tissue consisting of living cells embedded in a rubbery matrix with collagen fibers.

cartilaginous fish (*kar-ti-laj′-uh-nus*)
A fish that has a flexible skeleton made of cartilage.

cell body
The part of a cell, such as a neuron, that houses the nucleus and other organelles.

cell cycle
An ordered sequence of events (including interphase and the mitotic phase) that extends from the time a eukaryotic cell is first formed from a dividing parent cell until its own division into two cells.

cell cycle control system
A cyclically operating set of proteins that triggers and coordinates events in the eukaryotic cell cycle.

cell division
The reproduction of a cell.

cell junction
A structure that connects animal cells to one another in a tissue.

cell plate
A membranous disk that forms across the midline of a dividing plant cell. During cytokinesis, the cell plate grows outward, accumulating more cell wall material and eventually fusing into a new cell wall.

cell theory
The theory that all living things are composed of cells and that all cells come from other cells.

cell wall
A protective layer external to the plasma membrane in plant cells, bacteria, fungi, and some protists; protects the cell and helps maintain its shape.

cell-mediated immune response
The type of adaptive immune response that involves T cells, lymphocytes that fight body cells infected with pathogens. *See also* humoral immune response.

cellular differentiation
Specialization in the structure and function of cells that occurs during the development of an organism; results from selective activation and deactivation of the cells' genes.

cellular respiration
The aerobic harvesting of energy from food molecules; the energy-releasing chemical breakdown of food molecules, such as glucose, and the storage of potential energy in a form that cells can use to perform work; involves glycolysis, the citric acid cycle, the electron transport chain, and chemiosmosis.

cellular slime mold
A type of protist that has unicellular amoeboid cells and a multicellular reproductive body in its life cycle.

cellulose (*sel′-yū-lōs*)
A large polysaccharide composed of many glucose monomers linked into cable-like fibrils that provide structural support in plant cell walls. Because cellulose cannot be digested by animals, it acts as fiber, or roughage, in the diet.

centipede
A carnivorous terrestrial arthropod that has one pair of long legs for each of its numerous body segments, with the front pair modified as poison claws.

central nervous system (CNS)
The integration and command center of the nervous system; the brain and, in vertebrates, the spinal cord.

central vacuole (*vak′-yū-ōl*)
A membrane-enclosed sac occupying most of the interior of a mature plant cell, having diverse roles in reproduction, growth, and development.

centromere (*sen′-trō-mer*)
The region of a chromosome where two sister chromatids are joined and where spindle microtubules attach during mitosis and meiosis. The centromere divides at the onset of anaphase during mitosis and anaphase II of meiosis.

centrosome (*sen′-trō-sōm*)
Material in the cytoplasm of a eukaryotic cell that gives rise to microtubules; important in mitosis and meiosis; functions as a microtubule-organizing center.

cephalopod
Member of a group of molluscs that includes squids and octopuses.

cerebellum (*sār′-ruh-bel′-um*)
Part of the vertebrate hindbrain; mainly a planning center that interacts closely with the cerebrum in coordinating body movement.

cerebral cortex (*suh-rē′-brul kor′-teks*)
A highly folded layer of tissue that forms the surface of the cerebrum. In humans, it contains integrating centers for higher brain functions, such as reasoning, speech, language, and imagination.

cerebrospinal fluid
(*suh-rē′-brō-spī′-nul*)
Fluid that surrounds, cushions, and nourishes the brain and spinal cord and protects them from infection.

cerebrum (*suh-rē′-brum*)
The largest, most sophisticated, and most dominant part of the vertebrate forebrain, made up of right and left cerebral hemispheres. The cerebrum contains the cerebral cortex.

cervix (*ser′-viks*)
The narrow neck at the bottom of the uterus, which opens into the vagina.

chaparral (*shap-uh-ral′*)
A terrestrial biome limited to coastal regions where cold ocean currents circulate offshore, creating mild, rainy winters and long, hot, dry summers; also known as the Mediterranean biome. Chaparral vegetation is adapted to fire.

character
A heritable feature that varies among individuals within a population, such as flower color in pea plants.

charophyte (*kār′-uh-fīt′*)
A member of the green algal group that shares features with land plants. Charophytes are considered the closest relatives of land plants; modern charophytes and modern plants likely evolved from a common ancestor.

chemical bond
An attraction between two atoms resulting from a sharing of outer-shell electrons or the presence of opposite charges on the atoms. The bonded atoms gain complete outer electron shells.

chemical cycling
The use and reuse of chemical elements such as carbon within an ecosystem.

chemical energy
Energy stored in the chemical bonds of molecules; a form of potential energy.

chemical reaction
A process leading to chemical changes in matter, involving the making and/or breaking of chemical bonds.

chemoreceptor (*kē′-mō-rē-sep′-ter*)
A sensory receptor that detects chemical changes within the body or a specific kind of chemical in the external environment; chemoreceptors are involved in our senses of taste and smell.

chemotherapy (*kē′-mo-ther′-uh-pē*)
Treatment for cancer in which drugs are administered to disrupt cell division of the cancer cells.

chiasma (*kī-az′-muh*)
(plural, **chiasmata**) The microscopically visible site where crossing over has occurred between chromatids of homologous chromosomes during prophase I of meiosis.

chlamydia
A common sexually transmitted disease caused by a bacterial infection. Its primary symptoms are genital discharge and burning during urination. It is easily treatable with antibiotics.

chlorophyll (*klor′-ō-fil*)
A light-absorbing pigment in chloroplasts that plays a central role in converting solar energy to chemical energy.

chlorophyll *a* (*klor′-ō-fil ā*)
A green pigment in chloroplasts that participates directly in the light reactions.

chloroplast (*klō′-rō-plast*)
An organelle found in plants and photosynthetic protists. Enclosed by two concentric membranes, a chloroplast absorbs sunlight and uses it to power the synthesis of organic food molecules (sugars).

chordate (*kōr′-dāt*)
An animal that at some point during its development has a dorsal, hollow nerve cord, a notochord, pharyngeal slits, and a post-anal tail. Chordates include lancelets, tunicates, and vertebrates.

chorion (*kōr′-ē-on*)
In animals, the outermost membrane protecting an embryo. In mammals, the chorion becomes part of the placenta.

chorionic villus (*kōr′-ē-on′-ik vil′-us*)
(plural, **villi**) An outgrowth of the chorion, containing embryonic blood vessels. As part of the placenta, chorionic villi absorb nutrients and oxygen from the mother's bloodstream and pass wastes into the mother's bloodstream.

chromatin (*krō′-muh-tin*)
The combination of DNA and proteins that constitutes chromosomes; often used to refer to the diffuse, very extended form taken by the chromosomes when a eukaryotic cell is not dividing.

chromosome (*krō′-muh-sōm*)
A gene-carrying structure found in the nucleus of a eukaryotic cell and most visible during mitosis and meiosis; also, the main gene-carrying structure of a prokaryotic cell. Each chromosome consists of one very long threadlike DNA molecule and associated proteins. *See also* chromatin.

chromosome theory of inheritance
A basic principle in biology stating that genes are located on chromosomes and that the behavior of chromosomes during meiosis accounts for inheritance patterns.

chyme (*kīm*)
A mixture of recently swallowed food and gastric juice.

ciliate (*sil′-ē-it*)
A type of protozoan (animal-like protist) that moves and feeds by means of cilia.

cilium (*sil′-ē-um*)
(plural, **cilia**) A short appendage that propels some protists through the water and moves fluids across the surface of many tissue cells in animals.

circulatory system
The organ system that transports materials such as nutrients, O_2, and hormones to body cells and transports CO_2 and other wastes from body cells.

citric acid cycle
The metabolic cycle that is fueled by acetyl CoA formed after glycolysis in cellular respiration. Chemical reactions in the cycle complete the metabolic breakdown of glucose molecules to carbon dioxide. The cycle occurs in the matrix of mitochondria and supplies most of the NADH molecules that carry energy to the electron transport chains. Also referred to as the Krebs cycle.

clade
An ancestral species and all its descendants—a distinctive branch in the tree of life.

cladistics (*kluh-dis′-tiks*)
The study of evolutionary history; specifically, an approach to systematics in which organisms are grouped by common ancestry.

class
In classification, the taxonomic category above order.

cleavage (*klē-vij*)
(1) Cytokinesis in animal cells and in some protists, characterized by pinching in of the plasma membrane. (2) In animal development, the succession of rapid cell divisions without cell growth, converting the animal zygote to a ball of cells.

cleavage furrow
The first sign of cytokinesis during cell division in an animal cell; a shallow groove in the cell surface near the old metaphase plate.

clitoris (*klit′-uh-ris*)
An organ in the female that engorges with blood and becomes erect during sexual arousal.

clonal selection (*klōn′-ul*)
The production of a population of genetically identical lymphocytes (white blood cells) that recognize

and attack the specific antigen that stimulated their proliferation. Clonal selection is the mechanism that underlies the immune system's specificity and memory of antigens.

clone
As a verb, to produce genetically identical copies of a cell, organism, or DNA molecule. As a noun, the collection of cells, organisms, or molecules resulting from cloning; also (colloquially), a single organism that is genetically identical to another because it arose from the cloning of a somatic cell.

closed circulatory system
A circulatory system in which blood is confined to vessels and is kept separate from the interstitial fluid.

cnidarian (*nī-dār′-ē-an*)
An animal characterized by cnidocytes, radial symmetry, a gastrovascular cavity, and a polyp or medusa body form. Cnidarians includes hydras, jellies, sea anemones, and corals.

coccus (*kok′-us*)
(plural, **cocci**) A spherical prokaryotic cell.

cochlea (*kok′-lē-uh*)
A coiled tube in the inner ear that contains the hearing organ, the organ of Corti.

codominant
Expressing two different alleles of a gene in a heterozygote.

codon (*kō′-don*)
A three-nucleotide sequence in mRNA that specifies a particular amino acid or polypeptide termination signal; the basic unit of the genetic code.

coelom (*sē′-lōm*)
A body cavity completely lined by tissue derived from mesoderm.

cohesion (*kō-hē′-zhun*)
The attraction between molecules of the same kind.

collenchyma cell (*kuh-leng′-kuh-muh*)
In plants, a type of cell with a thick primary wall and no secondary wall, functioning mainly in supporting growing parts.

colon (*kō′-lun*)
Most of the length of the large intestine, the tubular portion of the vertebrate alimentary canal between the small intestine and the rectum; functions mainly in water absorption and the formation of feces.

community
All the organisms inhabiting and potentially interacting in a particular area; an assemblage of populations of different species.

community ecology
The study of how interactions between species affect community structure and organization.

comparative anatomy
The comparison of body structures in different species.

competitive exclusion principle
The concept that populations of two species cannot coexist in a community if their niches are nearly identical. Using resources more efficiently and having a reproductive advantage, one of the populations will eventually outcompete and eliminate the other.

complement protein
A defensive blood protein that attacks pathogens directly as part of innate internal defense. Complement proteins can enhance phagocytosis and cut holes in microbial membranes, causing the cells to burst.

complementary DNA (cDNA)
A DNA molecule made in vitro using mRNA as a template and the enzyme reverse transcriptase. A cDNA molecule therefore corresponds to a gene but lacks the introns present in the DNA of the genome.

complete digestive tract
A digestive tube with two openings, a mouth and an anus.

compost
A soil-like mixture of decomposed organic matter used to fertilize plants.

compound
A substance containing two or more elements in a fixed ratio; for example, table salt (NaCl) consists of one atom of the element sodium (Na) for every atom of chlorine (Cl).

concentration gradient
An increase or decrease in the density of a chemical substance within a given region. Cells often maintain concentration gradients of hydrogen ions across their membranes. When a gradient exists, the ions or other chemical substances involved tend to move from where they are more concentrated to where they are less concentrated.

condom
A flexible sheath, usually made of thin rubber or latex, designed to cover the penis during sexual intercourse for contraceptive purposes or as a means of preventing sexually transmitted diseases.

cone
(1) In vertebrates, a photoreceptor cell in the retina, stimulated by bright light and enabling color vision. (2) In conifers, a reproductive structure bearing pollen or ovules.

conifer (*kon′-uh-fer*)
A gymnosperm, or naked-seed plant, most of which produce cones.

coniferous forest (*kō-nif′-rus*)
A terrestrial biome characterized by conifers, cone-bearing evergreen trees.

connective tissue
Tissue consisting of cells held in an abundant extracellular matrix.

conservation biology
A goal-oriented science that seeks to understand and counter the loss of biodiversity.

conservation of energy
The principle that energy can neither be created nor destroyed.

consumer
An organism that obtains its food by eating plants or by eating animals that have eaten plants.

contraception
The deliberate prevention of pregnancy.

controlled experiment
A component of the process of science whereby a scientist carries out two parallel tests, an experimental test and a control test. The experimental test differs from the control by one factor, the variable.

convergent evolution
The evolution of similar features in different evolutionary lineages, which can result from living in very similar environments.

coral reef
Tropical marine biome characterized by hard skeletal structures secreted primarily by the resident cnidarians.

cork
The outermost protective layer of a plant's bark, produced by the cork cambium.

cork cambium
Meristem tissue that produces cork cells during secondary growth of a plant.

cornea (*kor′-nē-uh*)
The transparent front portion of the sclera that admits light into the vertebrate eye.

coronary artery (*kōr′-uh-nār-ē*)
A large blood vessel that conveys blood from the aorta to the tissues of the heart.

corpus callosum (*kor′-pus kuh-lō′-sum*)
A thick band of nerve fibers that connects the right and left cerebral hemispheres, enabling them to process information together.

corpus luteum (*kor′-pus lū′-tē-um*)
A small body of endocrine tissue that develops from an ovarian follicle after ovulation. The corpus luteum secretes progesterone and estrogen during pregnancy.

cortex
In plants, the ground tissue system of a root, which stores food and absorbs water and minerals that have passed through the epidermis. *See also* adrenal cortex; cerebral cortex.

corticosteroid
One of a family of steroid hormones, including glucocorticoids, synthesized and secreted by the adrenal cortex.

cotyledon (*kot′-uh-lē′-don*)
The first leaf that appears on an embryo of a flowering plant; a seed leaf. Monocot embryos have one cotyledon; dicot embryos have two.

covalent bond (*kō-vā′-lent*)
An attraction between atoms that share one or more pairs of outer-shell electrons.

crista (*kris′-tuh*)
(plural, **cristae**) A fold of the inner membrane of a mitochondrion. Enzyme molecules embedded in cristae make ATP.

cross
The cross-fertilization of two different varieties of an organism or of two different species; also called hybridization.

crossing over
The exchange of segments between chromatids of homologous chromosomes during prophase I of meiosis.

crustacean
Member of a major arthropod group that includes lobsters, crayfish, crabs, shrimps, and barnacles.

cryptic coloration
Adaptive coloration that makes an organism difficult to spot against its background.

culture
The accumulated knowledge, customs, beliefs, arts, and other human products that are socially transmitted over the generations.

cuticle (*kyū′-tuh-kul*)
(1) In animals, a tough, nonliving outer layer of the skin. (2) In plants, a waxy coating on the surface of stems and leaves that helps retain water.

cystic fibrosis (*sis′-tik fī-brō′-sis*)
A genetic disease that occurs in people with two copies of a certain recessive allele; characterized by an excessive secretion of mucus and consequent vulnerability to infection; fatal if untreated.

cytokinesis (*sī′-tō-kuh-nē′-sis*)
The division of the cytoplasm to form two separate daughter cells. Cytokinesis usually occurs during telophase of mitosis, and the two processes (mitosis and cytokinesis) make up the mitotic (M) phase of the cell cycle.

cytokinin (*sī′-tō-kī′-nin*)
Any of a family of plant hormones that promote cell division, retard aging in flowers and fruits, and may counter the effects of auxins in regulating plant growth and development.

cytoplasm (*sī′-tō-plaz′-um*)
Everything inside a eukaryotic cell between the plasma membrane and the nucleus; consists of a semifluid medium and organelles; can also refer to the interior of a prokaryotic cell.

cytosine (C) (*sī′-tuh-sēn*)
A single-ring nitrogenous base found in DNA and RNA.

cytoskeleton
A meshwork of fine fibers in the cytoplasm of a eukaryotic cell; includes microfilaments, intermediate filaments, and microtubules.

cytosol (*sī′-tuh-sol*)
The fluid part of the cytoplasm, in which organelles are suspended.

cytotoxic T cell (*sī′-tō-tok′-sik*)
A type of lymphocyte that directly attacks body cells infected by pathogens.

D

decomposer
An organism that secretes enzymes that digest molecules in organic material and convert them to inorganic form.

dehydration (*dē-hī-drā′-shun*)
A chemical process in which a polymer forms when monomers are linked by the removal of water molecules. One molecule of water is removed for each pair of monomers linked. A dehydration reaction is essentially the reverse of a hydrolysis reaction.

denaturation (*dē-nā′-chuh-rā′-shun*)
A process in which a protein unravels, losing its specific conformation and hence its function; can be caused by changes in pH or salt concentration or by high temperature; also refers to the separation of the two strands of the DNA double helix, caused by similar factors.

dendrite (*den′-drīt*)
A short, branched neuron fiber that receives signals and conveys them from its tip inward, toward the rest of the neuron.

density-dependent factor
A limiting factor whose effects intensify with increasing population density.

density-independent factor
A limiting factor whose occurrence and effects are not related to population density.

dermal tissue system
In plants, the tissue system that forms an outer protective covering.

desert
A terrestrial biome characterized by low and unpredictable rainfall (less than 30 cm per year).

determinate growth
Termination of growth after reaching a certain size, as in most animals. *See also* indeterminate growth.

detritivore (*di-trī′-tuh-vor*)
An organism that consumes dead organic matter (detritus).

detritus (*di-trī′-tus*)
Dead organic matter.

diabetes mellitus (*dī′-uh-bē′-tis mel′-uh-tus*)
A human hormonal disease in which body cells cannot absorb enough glucose from the blood and become energy starved. Body fats and proteins are then consumed for their energy. Insulin-dependent diabetes results when the pancreas does not produce insulin. Non-insulin-dependent diabetes results when body cells fail to respond to insulin. A third type of diabetes, called gestational diabetes, can affect any pregnant woman, even one who has never shown symptoms of diabetes before.

dialysis (*dī-al′-uh-sis*)
Separation and disposal of metabolic wastes from the blood by mechanical means; an artificial method of performing the functions of the kidneys.

diaphragm (*dī′-uh-fram*)
(1) The sheet of muscle separating the chest cavity from the abdominal cavity in mammals. Its contraction expands the chest cavity, and its relaxation reduces it. (2) A dome-shaped rubber cap that covers a woman's cervix, serving as a barrier method of contraception.

diastole (*dī-as′-tuh-lē*)
The stage of the cardiac cycle in which the heart muscle is relaxed, allowing the chambers to fill with blood. *See also* systole.

diatom (*dī′-uh-tom*)
A unicellular photosynthetic alga with a unique glassy cell wall containing silica.

dicot (*dī′-kot*)
A flowering plant whose embryos have two seed leaves, or cotyledons.

diffusion
The spontaneous movement of particles of any kind down a concentration gradient; that is, movement of particles from where they are more concentrated to where they are less concentrated.

digestion
The mechanical and chemical breakdown of food into molecules small enough for the body to absorb; the second stage of food processing, following ingestion.

digestive tract
A digestive compartment with two openings: a mouth for the entrance of food and an anus for the exit of undigested wastes. Most animals, including humans, have a digestive tract, more commonly called an alimentary canal.

dihybrid cross (*dī′-hī′-brid*)
A mating of individuals differing at two genetic loci.

dinoflagellate (*dī′-nō-flaj′-uh-let*)
A unicellular photosynthetic alga with two flagella situated in perpendicular grooves in cellulose plates covering the cell.

diploid (*dip′-loid*)
Containing two sets of chromosomes (pairs of homologous chromosomes) in each cell, one set inherited from each parent; referring to a 2*n* cell.

directional selection
Natural selection that acts in favor of the individuals at one end of a phenotypic range.

disaccharide (*dī-sak′-uh-rīd*)
A sugar molecule consisting of two monosaccharides linked by a dehydration reaction.

discovery science
The process of scientific inquiry that focuses on using observations to describe nature. *See also* hypothesis-driven science.

disruptive selection
Natural selection that favors extreme over intermediate phenotypes.

disturbance
In an ecological sense, a force that damages a biological community, at least temporarily, by destroying organisms and altering the availability of resources needed by organisms in the community. Disturbances such as fires and storms play a pivotal role in structuring many biological communities.

DNA Deoxyribonucleic acid (*dē-ok′-si-rī′-bō-nū-klā′-ik*)
The genetic material that organisms inherit from their parents; a double-stranded helical macromolecule consisting of nucleotide monomers with deoxyribose sugar, a phosphate group, and the nitrogenous bases adenine (A), cytosine (C), guanine (G), and thymine (T). *See also* gene.

DNA ligase (*lī′-gās*)
An enzyme, essential for DNA replication, that catalyzes the covalent bonding of adjacent DNA nucleotides; used in genetic engineering to paste a specific piece of DNA containing a gene of interest into a bacterial plasmid or other vector.

DNA microarray
A glass slide containing thousands of different kinds of single-stranded DNA fragments arranged in an array (grid). Tiny amounts of DNA fragments, representing different genes, are attached to the glass slide. These fragments are tested for hybridization with various samples of cDNA molecules, thereby measuring the expression of thousands of genes at one time.

DNA polymerase (*puh-lim′-er-ās*)
An enzyme that assembles DNA nucleotides into polynucleotides using a preexisting strand of DNA as a template.

DNA profiling
A procedure that analyzes an individual's unique collection of genetic markers using PCR and gel electrophoresis. DNA profiling can be used to determine whether two samples of genetic material were derived from the same individual.

DNA technology
Methods used to study or manipulate genetic material.

domain
A taxonomic category above the kingdom level. The three domains of life are Archaea, Bacteria, and Eukarya.

dominant allele
In a heterozygote, the allele that determines the phenotype with respect to a particular gene.

dorsal, hollow nerve cord
One of the four hallmarks of chordates; the chordate brain and spinal cord.

double circulation system
A circulation scheme with separate pulmonary and systemic circuits.

double fertilization
In flowering plants, the formation of both a zygote and a cell with a triploid nucleus, which develops into the endosperm.

double helix
The form assumed by DNA in living cells, referring to its two adjacent polynucleotide strands wound into a spiral shape.

Down syndrome
A human genetic disorder resulting from a condition called trisomy 21, the presence of an extra chromosome 21; characterized by heart and respiratory defects and varying degrees of mental retardation.

duodenum (*dū-ō-dē′-num*)
The first portion of the vertebrate small intestine after the stomach, where chyme from the stomach is mixed with bile and digestive enzymes.

E

eardrum
A sheet of connective tissue separating the outer ear from the middle ear. The eardrum vibrates when stimulated by sound waves and passes the vibrations to the middle ear.

earthworm
A type of annelid, or segmented worm, that extracts nutrients from soil.

echinoderm (*ih-kī′-nuh-derm*)
Member of a group of slow-moving or stationary marine animals characterized by a rough or spiny skin, a water vascular system, typically an endoskeleton, and radial symmetry in adults. Echinoderms include sea stars, sea urchins, and sand dollars.

ecological footprint
An estimate of the amount of land required to provide the raw materials an individual or a population consumes, including food, fuel, water, housing, and waste disposal.

ecological niche
The sum of a species' use of the biotic and abiotic resources in its environment.

ecological succession
The process of biological community change resulting from disturbance; transition in the species composition of a biological community, often following a flood, fire, or volcanic eruption. *See also* primary succession; secondary succession.

ecology
The scientific study of the interactions between organisms and their environments.

ecosystem (*ē′-kō-sis-tem*)
All the organisms in a given area, along with the nonliving (abiotic) factors with which they interact; a biological community and its physical environment.

ecosystem ecology
The study of energy flow and the cycling of chemicals among the various biotic and abiotic factors in an ecosystem.

ecosystem services
Functions performed by an ecosystem that directly or indirectly benefit people.

ectotherm (*ek′-tō-therm*)
An animal that warms itself mainly by absorbing heat from its surroundings.

effector cell
A short-lived lymphocyte that has an immediate effect against a specific pathogen; a cell capable of carrying out some action in response to a command from the nervous system.

egg
A female gamete.

ejaculation (*ih-jak′-yū-lā′-shun*)
The expulsion of sperm-containing fluid (semen) from the penis.

electrocardiogram (ECG or EKG)
A record of the electrical impulses that travel through heart muscle during the cardiac cycle.

electromagnetic receptor
A sensory receptor that detects energy of different wavelengths, such as magnetism and light.

electromagnetic spectrum
The full range of radiation, from the very short wavelengths of gamma rays to the very long wavelengths of radio signals.

electron
A subatomic particle with a single unit of negative electrical charge. One or more electrons move around the nucleus of an atom.

electron microscope (EM)
An instrument that focuses an electron beam through or onto the surface of a specimen. An electron microscope achieves a thousandfold greater resolving power than a light microscope; the most powerful EM can distinguish objects as small as 0.2 nm (2×10^{-10} m).

electron transport
A redox (oxidation-reduction) reaction in which one or more electrons are transferred to carrier molecules. A series of such reactions, called an electron transport chain, can release the energy stored in high-energy molecules such as glucose. *See also* electron transport chain.

electron transport chain
A series of electron carrier molecules that shuttle electrons during the redox reactions that release energy used to make ATP; located in the inner membrane of mitochondria, the thylakoid membrane of chloroplasts, and the plasma membrane of prokaryotes.

element
A substance that cannot be broken down into other substances by chemical means. Scientists recognize 92 chemical elements occurring in nature.

elimination
The passing of undigested material out of the digestive compartment; the fourth stage of food processing, following absorption.

embryo (*em′-brē-ō*)
A developing stage of a multicellular organism. In humans, the stage in the development of offspring from the first division of the zygote until body structures begin to appear, about the 9th week of pregnancy.

embryo sac
The female gametophyte contained in the ovule of a flowering plant.

embryonic stem cell (ES cell)
Any of the cells in the early animal embryo that differentiate during development to give rise to all the kinds of specialized cells in the body.

emerging virus
A virus that has appeared suddenly or has recently come to the attention of medical scientists.

endangered species
As defined in the U.S. Endangered Species Act, a species that is in danger of extinction throughout all or a significant portion of its range.

endemic species
A species whose distribution is limited to a specific geographic area.

endocrine gland (*en′-dō-krin*)
A gland that synthesizes hormone molecules and secretes them directly into the bloodstream.

endocrine system
The body's main system for internal chemical regulation, consisting of all hormone-secreting cells; cooperates with the nervous system in regulating body functions and maintaining homeostasis.

endocytosis (*en′-dō-sī-tō′-sis*)
The movement of materials from the external environment into the cytoplasm of a cell via vesicles or vacuoles.

endodermis
The innermost layer (a one-cell-thick cylinder) of the cortex of a plant root. The endodermis forms a selective barrier, determining which substances pass from the cortex into the vascular tissue.

endomembrane system
A network of organelles that partitions the cytoplasm of eukaryotic cells into functional compartments. Some of the organelles are structurally connected to each other, whereas others are structurally separate but functionally connected by the traffic of vesicles among them.

endometrium (*en′-dō-mē′-trē-um*)
The inner lining of the uterus in mammals, richly supplied with blood vessels that provide the maternal part of the placenta and nourish the developing embryo.

endoplasmic reticulum (ER) (*reh-tik′-yuh-lum*)
An extensive membranous network in a eukaryotic cell, continuous with the outer nuclear membrane and composed of ribosome-studded (rough) and ribosome-free (smooth) regions. *See also* rough ER; smooth ER.

endorphin (*en-dōr′-fin*)
A pain-inhibiting hormone produced by the anterior pituitary; also serves as a neurotransmitter.

endoskeleton
A hard interior skeleton located within the soft tissues of an animal; found in all vertebrates and a few invertebrates (such as echinoderms).

endosperm
In flowering plants, a nutrient-rich mass formed by the union of a sperm cell with the diploid central cell of the embryo sac during double fertilization; provides nourishment to the developing embryo in the seed.

endospore
A thick-coated, protective cell produced within a prokaryotic cell exposed to harsh conditions.

endosymbiosis (*en′-dō-sim-bē-ō′-sis*)
Symbiotic relationship in which one species resides within another species. The mitochondria and chloroplasts of eukaryotic cells probably evolved from symbiotic associations between small prokaryotic cells living inside larger ones.

endotherm
An animal that derives most of its body heat from its own metabolism.

endotoxin
A poisonous component of the outer membrane of certain bacteria.

energy
The capacity to cause change, or to move matter in a direction it would not move if left alone.

energy flow
The passage of energy through the components of an ecosystem.

enhancer
A eukaryotic DNA sequence that helps stimulate the transcription of a gene at some distance from it. An enhancer functions by means of a transcription factor called an activator, which binds to it and then to the rest of the transcription apparatus. *See also* silencer.

entropy (*en′-truh-pē*)
A measure of disorder, or randomness. One form of disorder is heat, which is random molecular motion.

enzyme (*en′-zīm*)
A protein that serves as a biological catalyst, changing the rate of a chemical reaction without itself being changed in the process.

enzyme inhibitor
A chemical that interferes with an enzyme's activity by changing the enzyme's shape, either by plugging up the active site or by binding to another site on the enzyme.

epinephrine (*ep′-uh-nef′-rin*)
An amine hormone (also called adrenaline) that is secreted by the adrenal medulla and that prepares body organs for "fight or flight"; also serves as a neurotransmitter.

epithelial tissue (*ep′-uh-thē′-lē-ul*)
A sheet of tightly packed cells lining organs and cavities; also called epithelium.

epithelium
(plural, **epithelia**) *See* epithelial tissue.

equilibrial life history (*ē-kwi-lib′-rē-ul*)
The pattern of reaching sexual maturity slowly and producing few offspring but caring for the young; often seen in long-lived, large-bodied species.

erythrocyte (*ih-rith′-ruh-sīt*)
See red blood cell.

esophagus (*ih-sof′-uh-gus*)
The channel through which food passes in a digestive tube, connecting the pharynx to the stomach.

essential amino acid
Any amino acid that an animal cannot synthesize itself and must obtain from food. Eight amino acids are essential for the human adult.

essential element
In plants, a chemical element required for the plant to complete its life cycle (to grow from a seed and produce another generation of seeds).

essential fatty acid
An unsaturated fatty acid that animals need but cannot make.

essential nutrient
A substance that an organism must absorb in preassembled form because it cannot synthesize the nutrient from any other material. Humans require vitamins, minerals, essential amino acids, and essential fatty acids.

estrogen (*es′-trō-jen*)
One of several chemically similar sex hormones secreted by the gonads. Estrogen maintains the female reproductive system and promotes the development of female body features.

estuary (*es′-chuh-wār-ē*)
The area where a freshwater stream or river merges with seawater.

ethylene
A gas that functions as a hormone in plants, triggering aging responses such as fruit ripening and leaf drop.

eudicot (*yū-dī′-kot*)
Member of a group consisting of the vast majority of flowering plants that have two cotyledons (embryonic seed leaves).

Eukarya (*yū-kār′-yuh*)
The domain of eukaryotes, organisms made up of eukaryotic cells; includes all of the protists, plants, fungi, and animals.

eukaryote (*yū-kār′-ē-ōt*)
An organism characterized by eukaryotic cells. *See also* eukaryotic cell.

eukaryotic cell (*yū-kār-ē-ot′-ik*)
A type of cell that has a membrane-enclosed nucleus and other membrane-enclosed organelles. All organisms except bacteria and archaea are composed of eukaryotic cells.

Eustachian tube (*yū-stā′-shun*)
An air passage between the middle ear and throat that equalizes air pressure on either side of the eardrum.

eutherian (*yū-thēr′-ē-un*)
See placental mammal.

evaporative cooling
A property of water whereby a body becomes cooler as water evaporates from it.

evo-devo
Evolutionary developmental biology, which studies the evolution of developmental processes in multicellular organisms.

evolution
Descent with modification; genetic change in a population or species over generations; the heritable changes that have produced Earth's diversity of organisms.

evolutionary adaptation
A population's increase in the frequency of traits suited to the environment.

evolutionary tree
A branching diagram that reflects a hypothesis about evolutionary relationships between groups of organisms.

excretion (*ek-skrē′-shun*)
The disposal of nitrogen-containing metabolic wastes.

exocytosis (*ek′-sō-sī-tō′-sis*)
The movement of materials out of the cytoplasm of a cell via membranous vesicles or vacuoles.

exon (*ek′-son*)
In eukaryotes, a coding portion of a gene. *See also* intron.

exoskeleton
A hard, external skeleton that protects an animal and provides points of attachment for muscles.

exotoxin
A poisonous protein secreted by certain bacteria.

exponential population growth
A model that describes the expansion of a population in an ideal, unlimited environment.

extracellular matrix
The meshwork that surrounds animal cells, consisting of a web of protein and polysaccharide fibers embedded in a liquid, jelly, or solid.

F

F_1 generation
The offspring of two parental (P generation) individuals. F_1 stands for first filial.

F_2 generation
The offspring of the F_1 generation. F_2 stands for second filial.

facilitated diffusion
The passage of a substance across a biological membrane down its concentration gradient, aided by specific transport proteins.

family
In classification, the taxonomic category above genus.

farsightedness
An inability to focus on close objects; occurs when the eyeball is shorter than normal and the focal point of the lens is behind the retina; also called hyperopia.

fat
A large lipid molecule made from an alcohol called glycerol and three fatty acids; a triglyceride. Most fats function as energy-storage molecules.

feces
The wastes of the digestive tube.

fermentation
The anaerobic harvest of food by some cells.

fern
Any of a group of seedless vascular plants.

fertilization
The union of a haploid sperm cell with a haploid egg cell, producing a zygote.

fertilizer
A compound applied to the soil to promote plant growth.

fetus (*fē′-tus*)
A developing human from the 9th week of pregnancy until birth. The fetus has all the major structures of an adult.

fever
An abnormally high internal body temperature, usually the result of an infection.

fibrin (*fī′-brin*)
The activated form of the blood-clotting protein fibrinogen, which aggregates into threads that form the fabric of a blood clot.

fibrinogen (*fī-brin′-uh-jen*)
The plasma protein that is activated to form a clot when a blood vessel is injured.

fibrous connective tissue
A dense tissue with large numbers of collagen fibers organized into parallel bundles. This is the dominant tissue in tendons and ligaments.

filtrate
Fluid extracted by the excretory system from the blood or body cavity. The excretory system produces urine from the filtrate after extracting valuable solutes from it and concentrating it.

filtration
In the vertebrate kidney, the extraction of water and small solutes, including metabolic wastes, from the blood by the nephrons.

fission
A means of asexual reproduction whereby a parent separates into two or more genetically identical individuals of about equal size.

flagellate (*flaj′-uh-lit*)
A protozoan (animal-like protist) that moves by means of one or more flagella.

flagellum (*fluh-jel′-um*)
(plural, **flagella**) A long appendage that propels protists through the water and moves fluids across the surface of many tissue cells in animals. A cell may have one or more flagella.

flatworm
A bilateral animal with a thin, flat body form, a gastrovascular cavity with a single opening, and no body cavity. Flatworms include planarians, flukes, and tapeworms.

flower
In an angiosperm, a short stem with four sets of modified leaves, bearing structures that function in sexual reproduction.

fluid mosaic
A description of membrane structure, depicting a cellular membrane as a mosaic of diverse protein molecules embedded in a fluid bilayer of phospholipid molecules.

follicle (*fol′-uh-kul*)
A cluster of cells surrounding, protecting, and nourishing a developing egg cell in the ovary. The follicle also secretes estrogen.

food chain
The sequence of food transfers between the trophic levels of a community, beginning with the producers.

food web
A network of interconnecting food chains.

foram
A marine protozoan (animal-like protist) that secretes a shell and extends pseudopodia through pores in its shell.

forensics
The scientific analysis of evidence for crime scene investigations and other legal proceedings.

fossil
A preserved imprint or remains of an organism that lived in the past.

fossil fuel
An energy deposit formed from the fossilized remains of long-dead plants and animals.

fossil record
The ordered sequence of fossils as they appear in the rock layers, marking the passing of geologic time.

founder effect
The genetic drift resulting from the establishment of a small, new population whose gene pool differs from that of the parent population.

fruit
A ripened, thickened ovary of a flower, which protects dormant seeds and aids in their dispersal.

functional group
A group of atoms that form the chemically reactive part of an organic molecule. A particular functional group usually behaves similarly in different chemical reactions.

fungus
(plural, **fungi**) A chemo-heterotrophic eukaryote that digests its food externally and absorbs the resulting small nutrient molecules. Most fungi consist of a netlike mass of filaments called hyphae. Molds, mushrooms, and yeasts are examples of fungi.

G

gallbladder
An organ that stores bile and releases it as needed into the small intestine.

gametangium (*gam′-uh-tan′-jē-um*)
(plural, **gametangia**) A reproductive organ that houses and protects the gametes of a plant.

gamete (*gam′-ēt*)
A sex cell; a haploid egg or sperm. The union of two gametes of opposite sex (fertilization) produces a zygote.

gametogenesis
The creation of gametes within the gonads.

gametophyte (*guh-mē′-tō -fīt*)
The multicellular haploid form in the life cycle of organisms undergoing alternation of generations; results from a union of spores and mitotically produces haploid

gametes that unite and grow into the sporophyte generation.

gastric juice
The collection of fluids secreted by the epithelium lining the stomach.

gastropod
Member of the largest group of molluscs, including snails and slugs.

gastrovascular cavity
A digestive compartment with a single opening that serves as both the entrance for food and the exit for undigested wastes; may also function in circulation, body support, and gas exchange. Jellies and hydras are examples of animals with a gastrovascular cavity.

gastrula (*gas′-trū-luh*)
The embryonic stage resulting from gastrulation in animal development. Most animals have a gastrula made up of three layers of cells: ectoderm, endoderm, and mesoderm.

gastrulation (*gas′-trū-lā′-shun*)
The phase of embryonic development that transforms the blastula (blastocyst in mammals) into a gastrula. Gastrulation adds more cells to the embryo and sorts the cells into distinct cell layers.

gel electrophoresis (*jel′ e-lek′-trō-fōr-ē′-sis*)
A technique for sorting macromolecules. A mixture of molecules is placed on a gel between a positively charged electrode and a negatively charged one; negative charges on the molecules are attracted to the positive electrode, and the molecules migrate toward that electrode. The molecules separate in the gel according to their rates of migration.

gene
A unit of inheritance in DNA (or RNA, in some viruses) consisting of a specific nucleotide sequence that programs the amino acid sequence of a polypeptide. Most of the genes of a eukaryote are located in its chromosomal DNA; a few are carried by the DNA of mitochondria and chloroplasts.

gene cloning
The production of multiple copies of a gene.

gene expression
The process whereby genetic information flows from genes to proteins; the flow of genetic information from the genotype to the phenotype: DNA → RNA → protein.

gene flow
The gain or loss of alleles from a population by the movement of individuals or gametes into or out of the population.

gene pool
All the genes in a population at any one time.

gene regulation
The turning on and off of specific genes within a living organism.

genetic code
The set of rules giving the correspondence between nucleotide triplets (codons) in mRNA and amino acids in protein.

genetic drift
A change in the gene pool of a population due to chance.

genetic engineering
The direct manipulation of genes for practical purposes.

genetic recombination
The production of offspring with gene combinations that differ from that found in either parent.

genetically modified (GM) organism
An organism that has acquired one or more genes by artificial means. If the gene is from another organism, typically of another species, the recombinant organism is also known as a transgenic organism.

genetics
The scientific study of heredity (inheritance).

genital herpes
A common sexually transmitted disease caused by a virus. The primary symptom is sores on the genitalia. Although outbreaks can be controlled with medication, genital herpes is incurable.

genomic library (*juh-nō′-mik*)
The entire collection of DNA segments from an organism's genome. Each segment is usually carried by a plasmid or phage.

genomics
The study of whole sets of genes and their interactions.

genotype (*jē′-nō-tīp*)
The genetic makeup of an organism.

genus (*jē′-nus*)
(plural, **genera**) In classification, the taxonomic category above species; the first part of a species' binomial; for example, *Homo*.

geologic time scale
A time scale established by geologists that reflects a consistent sequence of geologic periods, grouped into four divisions: Precambrian, Paleozoic, Mesozoic, and Cenozoic.

germinate
To initiate growth, as in a plant seed.

gestation (*jes-tā′-shun*)
Pregnancy; the state of carrying developing young within the female reproductive tract.

gibberellin (*jib′-uh-rel′-in*)
Any of a family of plant hormones that trigger the germination of seeds and interact with auxins in regulating growth and fruit development.

gill
An extension of the body surface of an aquatic animal, specialized for gas exchange and/or suspension feeding.

glucagon (*glū′-kuh-gon*)
A protein hormone, secreted by islet cells in the pancreas, that raises the level of glucose in the blood.

glucocorticoid (*glū′-kuh-kor′-tih-koyd*)
A corticosteroid hormone, secreted by the adrenal cortex, that increases the blood glucose level and helps maintain the body's response to long-term stress.

glycogen (*glī′-kō-jen*)
A complex, extensively branched polysaccharide made up of many glucose monomers; serves as an energy-storage molecule in liver and muscle cells.

glycolysis (*glī-kol′-uh-sis*)
The multistep chemical breakdown of a molecule of glucose into two molecules of pyruvic acid; the first stage of cellular respiration in all organisms; occurs in the cytoplasmic fluid.

Golgi apparatus (*gol′-jē*)
An organelle in eukaryotic cells consisting of stacks of membranous sacs that modify, store, and ship products of the endoplasmic reticulum.

gonad
An animal sex organ that produces gametes; an ovary or a testis.

granum (*gran′-um*)
(plural, **grana**) A stack of hollow disks formed of thylakoid membrane in a chloroplast. Grana are the sites where light energy is trapped by chlorophyll and converted to chemical energy during the light reactions of photosynthesis.

gravitropism (*grav′-uh-trō′-pizm*)
A plant's directional growth in response to gravity.

green alga
One of a group of photosynthetic protists that includes unicellular, colonial, and multicellular species. Green algae are the photosynthetic protists most closely related to plants.

greenhouse effect
The warming of the atmosphere caused by CO_2, CH_4, and other gases that absorb heat radiation and slow its escape from Earth's surface.

greenhouse gas
Any of the gases in the atmosphere that absorb heat radiation, including CO_2, methane, water vapor, and synthetic chlorofluorocarbons.

ground tissue system
A tissue that makes up the bulk of a plant, filling the space between the epidermis and the vascular tissue system. The ground tissue system fulfills a variety of functions, including storage, photosynthesis, and support.

growth factor
A protein secreted by certain body cells that stimulates other cells to divide.

guanine (G) (*gwa′-nēn*)
A double-ring nitrogenous base found in DNA and RNA.

guard cell
A specialized epidermal cell in plants that regulates the size of a stoma, allowing gas exchange between the surrounding air and the photosynthetic cells in the leaf.

gymnosperm (*jim′-nō-sperm*)
A naked-seed plant. Its seed is said to be naked because it is not enclosed in an ovary.

H

habitat
A place where an organism lives; a specific environment in which an organism lives.

haploid
Containing a single set of chromosomes; referring to an *n* cell.

Hardy-Weinberg equilibrium
The condition describing a nonevolving population (one that is in genetic equilibrium).

heart
(1) The chambered muscular organ in vertebrates that pumps blood received from the veins into the arteries, thereby maintaining the flow of blood through the entire circulatory system. (2) A similarly functioning structure in invertebrates.

heart attack
Damage or death of heart muscle tissue and the resulting failure of the heart to deliver enough blood to the body.

heart murmur
A hissing sound emitted by an abnormal heart, usually caused by a defective heart valve.

heart rate
The number of heartbeats per minute.

heat
The amount of kinetic energy contained in the movement of the atoms and molecules in a body of matter. Heat is energy in its most random form.

helper T cell
A type of lymphocyte that helps activate other T cells and helps stimulate B cells to produce antibodies.

hemoglobin (*hē′-muh-glō-bin*)
An iron-containing protein in red blood cells that reversibly binds O_2 and transports it to body tissues.

hemophilia (*hē′-muh-fil′-ē-uh*)
A human genetic disease caused by a sex-linked recessive allele and characterized by excessive bleeding following injury.

herbivore
An animal that eats mainly plants, algae, or phytoplankton. *See also* carnivore; omnivore.

herbivory
The consumption of plant parts or algae by an animal.

heredity
The transmission of traits from one generation to the next.

hermaphrodite (*her-maf′-rō-dīt*)
An individual that has both female and male reproductive systems, producing both sperm and eggs.

heterotroph (*het′-er-ō-trōf*)
An organism that cannot make its own organic food molecules from inorganic ingredients and must obtain them by consuming other organisms or their organic products; a consumer or a decomposer in a food chain.

heterozygous (*het′-er-ō-zī′-gus*)
Having two different alleles for a given gene.

hinge joint
A joint that allows movement in only one plane. In humans, examples include the elbow and knee.

histamine (*his′-tuh-mēn*)
A chemical alarm signal released by injured cells that causes blood vessels to dilate during an inflammatory response.

histone (*his′-tōn*)
A small protein molecule associated with DNA and important in DNA packing in the eukaryotic chromosome.

HIV
Human immunodeficiency virus; the retrovirus that attacks the human immune system and causes AIDS.

homeostasis (*hō′-mē-ō-stā′-sis*)
The steady state of body functioning; the tendency to maintain relatively constant conditions in the internal environment even when the external environment changes.

homeotic gene (*hō′-mē-ot′-ik*)
A master control gene that determines the identity of a body structure of a developing organism, presumably by controlling the developmental fate of groups of cells. (In plants, such genes are called organ identity genes).

hominin (*hah′-mi-nin*)
Any anthropoid on the human branch of the evolutionary tree, more closely related to humans than to chimpanzees.

homologous chromosomes (*hō-mol′-uh-gus*)
The two chromosomes that make up a matched pair in a diploid cell. Homologous chromosomes are of the same length, centromere position, and staining pattern and possess genes for the same characteristics at corresponding loci. One homologous chromosome is inherited from the organism's father, the other from the mother.

homology (*hō-mol′-uh-jē*)
Anatomical similarity due to common ancestry.

homozygous (*hō′-mō-zī′-gus*)
Having two identical alleles for a given gene.

hormone
In multicellular organisms, a regulatory chemical that travels in body fluids from its production site to other sites, where target cells respond to the regulatory signal.

host
An organism that is exploited by a parasite or pathogen.

human gene therapy
A recombinant DNA procedure intended to treat disease by altering an afflicted person's genes.

Human Genome Project
An international collaborative effort that sequenced the DNA of the entire human genome.

human growth hormone (HGH)
A protein hormone, secreted by the anterior pituitary, that promotes development and growth and stimulates metabolism.

humoral immune response
The type of adaptive immune response that involves secretion of antibodies into the blood and lymph by effector B cells. These antibodies fight bacteria and viruses in body fluids. *See also* cell-mediated immune response.

Huntington's disease
A human genetic disease caused by a dominant allele; characterized by uncontrollable body movements and degeneration of the nervous system; usually fatal 10 to 20 years after the onset of symptoms.

hybrid
The offspring of parents of two different species or of two different varieties of one species; the offspring of two parents that differ in one or more inherited traits; an individual that is heterozygous for one or more pairs of genes.

hydrocarbon
A chemical compound composed only of the elements carbon and hydrogen.

hydrogen bond
A type of weak chemical bond formed when a partially positive hydrogen atom from one polar molecule is attracted to the partially negative atom in another molecule (or in another part of the same molecule).

hydrogenation
The process of converting unsaturated fats to saturated fats by adding hydrogen.

hydrolysis (*hī-drol′-uh-sis*)
A chemical process in which macromolecules are broken down by the chemical addition of water molecules to the bonds linking their monomers; an essential part of digestion. A hydrolysis reaction is the opposite of a dehydration reaction.

hydrophilic (*hī′-drō-fil′-ik*)
"Water-loving"; pertaining to polar, or charged, molecules (or parts of molecules), which are soluble in water.

hydrophobic (*hī′-drō-fō′-bik*)
"Water-fearing"; pertaining to nonpolar molecules (or parts of molecules), which do not dissolve in water.

hymen
A thin membrane that partly covers the vaginal opening in the human female and is ruptured by sexual intercourse or other vigorous activity.

hypercholesterolemia (*hī′-per-kō-les′-tur-ah-lēm′-ē-uh*)
An inherited human disease characterized by an excessively high level of cholesterol in the blood.

hypertension
Abnormally high blood pressure consisting of a persistent systolic blood pressure higher than 140 and/or diastolic blood pressure higher than 90. This condition can lead to a variety of serious cardiovascular disorders.

hypertonic
In comparing two solutions, referring to the one with the greater concentration of solutes.

hypha (*hī′-fuh*)
(plural, **hyphae**) One of many filaments making up the body of a fungus.

hypothalamus (*hī′-pō-thal′-uh-mus*)
The main control center of the endocrine system, located in the vertebrate forebrain. The hypothalamus functions in maintaining homeostasis, especially in coordinating the endocrine and nervous systems. It synthesizes hormones secreted by the posterior pituitary and regulates the secretion of hormones by the anterior pituitary.

hypothesis (*hī-poth′-uh-sis*)
(plural, **hypotheses**) A tentative explanation that a scientist proposes for a specific phenomenon that has been observed.

hypothesis-driven science
The process of scientific inquiry that uses the steps of the scientific method to answer questions about nature. *See also* discovery science; scientific method.

hypotonic
In comparing two solutions, referring to the one with the lower concentration of solutes.

I

immune system
The body's system of defenses against infectious disease.

immunodeficiency disease
An immunological disorder in which the body lacks one or more components of the immune system, making a person susceptible to infectious agents that would not ordinarily cause a problem.

impotence
The inability to maintain an erection; also called erectile dysfunction.

in vitro fertilization (IVF) (*vē′-tro*)
Uniting sperm and egg in a laboratory container, followed by the placement of a resulting early embryo into the mother's uterus.

inbreeding
The mating of close relatives.

incomplete dominance
A type of inheritance in which the phenotype of a heterozygote (*Aa*) is intermediate between the phenotypes of the two types of homozygotes (*AA* and *aa*).

indeterminate growth
Growth that continues throughout life, as in most plants. *See also* determinate growth.

induced fit
The interaction between a substrate molecule and the active site of an enzyme, which changes shape slightly to embrace the substrate and catalyze the reaction.

induction
During embryonic development, the influence of one group of cells on an adjacent group of cells.

infertility
The inability to conceive after one year of regular, unprotected sexual intercourse.

inflammatory response
An example of internal innate defense involving the release of histamine and other chemical alarm signals, which trigger increased blood flow, a local increase in white blood cells, and fluid leakage from the blood. The results include redness, heat, and swelling in the affected tissues.

ingestion
The act of eating; the first stage of food processing.

innate defense
An immune system defense that is always present in its final form and ready to act.

inner ear
One of three main regions of the human ear; includes the cochlea, which contains the organ of Corti, the hearing organ.

insect
An arthropod that usually has three body segments (head, thorax, and abdomen), three pairs of legs, and one or two pairs of wings.

insulin
A protein hormone, secreted by islet cells in the pancreas, that lowers the level of glucose in the blood.

integration
The interpretation of sensory signals and the formulation of responses within the central nervous system.

interferon (*in′-ter-fēr′-on*)
A defensive protein that is produced by virus-infected cells and that helps other cells resist viruses as part of internal innate defense.

interneuron (*in′-ter-nūr′-on*)
A nerve cell, entirely within the central nervous system, that integrates sensory signals and may relay command signals to motor neurons.

internode
The portion of a plant stem between two nodes.

interphase
The phase in the eukaryotic cell cycle when the cell is not actually dividing. During interphase, cellular metabolic activity is high, chromosomes and organelles are duplicated, and cell size may increase. Interphase accounts for 90% of the cell cycle. *See also* mitosis.

interspecific competition
Competition between populations of two or more species that require similar limited resources.

interspecific interaction
Any interaction between members of different species.

interstitial fluid (*in′-ter-stish′-ul*)
An aqueous solution that surrounds body cells and through which materials pass back and forth between the blood and the body tissues.

intertidal zone (*in′-ter-tīd′-ul*)
A shallow zone where the waters of an estuary or ocean meet land.

intraspecific competition
Competition between individuals of the same species for the same limited resources.

intron (*in′-tron*)
In eukaryotes, a nonexpressed (noncoding) portion of a gene that is excised from the RNA transcript. *See also* exon.

invasive species
A non-native species that has spread far beyond the original point of introduction and causes environmental or economic damage by colonizing and dominating suitable habitats.

invertebrate
An animal that does not have a backbone.

ion (*ī′-on*)
An atom or molecule that has gained or lost one or more electrons, thus acquiring an electrical charge.

ionic bond (*ī-on′-ik*)
An attraction between two ions with opposite electrical charges. The electrical attraction of the opposite charges holds the ions together.

iris
The colored part of the vertebrate eye, formed by the anterior portion of the pigmented layer called the choroid.

isomer (*ī′-sō-mer*)
One of two or more molecules with the same molecular formula but different structures and thus different properties.

isotonic (*ī-sō-ton′-ik*)
Having the same solute concentration as another solution.

isotope (*ī′-sō-tōp*)
A variant form of an atom. Isotopes of an element have the same number of protons and electrons but different numbers of neutrons.

K

karyotype (*kār′-ē-ō-tīp*)
A display of micrographs of the metaphase chromosomes of a cell, arranged by size and centromere position.

keystone species
A species whose impact on its community is much larger than its biomass or abundance indicates.

kilocalorie (kcal)
A quantity of heat equal to 1,000 calories. Used to measure the energy content of food, it is usually called a "Calorie."

kinetic energy (*kuh-net′-ik*)
Energy of motion. Moving matter performs work by transferring its motion to other matter, such as leg muscles pushing bicycle pedals.

kingdom
In classification, the broad taxonomic category above phylum.

L

labia majora (*lā′-bē-uh muh-jor′-uh*)
A pair of outer thickened folds of skin that protect the female genital region.

labia minora (*lā′-bē-uh mi-nor′-uh*)
A pair of inner folds of skin bordering and protecting the female genital region.

labor
A series of strong, rhythmic uterine contractions that expels a baby out of the uterus and vagina during childbirth.

lancelet
One of a group of bladelike invertebrate chordates.

landscape
A regional assemblage of interacting ecosystems.

landscape ecology
The application of ecological principles to the study of land-use patterns; the scientific study of the biodiversity of interacting ecosystems.

large intestine
The tubular portion of the vertebrate alimentary canal between the small intestine and the anus. *See also* colon.

larynx (*lār′-inks*)
The voice box, containing the vocal cords.

lateral line system
A row of sensory organs along each side of a fish's body. Sensitive to changes in water pressure, it enables a fish to detect minor vibrations in the water.

law of independent assortment
A general rule of inheritance, first proposed by Gregor Mendel, that states that when gametes form during meiosis, each pair of alleles for a particular character segregate (separate) independently of each other pair.

law of segregation
A general rule of inheritance, first proposed by Gregor Mendel, that states that the two alleles in a pair segregate (separate) into different gametes during meiosis.

leaf
The main site of photosynthesis in a plant; consists of a flattened blade and a stalk (petiole) that joins the leaf to the stem.

leech
A type of annelid, or segmented worm, that typically lives in fresh water.

lens
The disklike structure in an eye that focuses light rays onto the retina.

leukemia (*lū-kē′-mē-ah*)
Cancer of the white blood cells (leukocytes), characterized by excessive production of these cells, resulting in an abnormally high number in the blood.

leukocyte (*lū′-kō-sīt*)
See white blood cell.

lichen (*lī′-ken*)
A mutually beneficial symbiotic association between a fungus and an alga or between a fungus and a cyanobacterium.

life
The set of common characteristics that distinguish living organisms from non-living matter, including such properties and processes as order, regulation, growth and development, energy utilization, response to the environment, reproduction, and the capacity to evolve over time.

life cycle
The entire sequence of stages in the life of an organism, from the adults of one generation to the adults of the next.

life history
The traits that affect an organism's schedule of reproduction and survival.

life table
A listing of survivals and deaths in a population in a particular time period and predictions of how long, on average, an individual of a given age will live.

ligament
A type of fibrous connective tissue that joins bones together at joints.

light microscope (LM)
An optical instrument with lenses that refract (bend) visible light to magnify images and project them into a viewer's eye or onto photographic film.

light reactions
The first of two stages in photosynthesis, the steps in which solar energy is absorbed and converted to chemical energy in the form of ATP and NADPH. The light reactions power the sugar-producing Calvin cycle but produce no sugar themselves.

lignin (*lig′-nin*)
A chemical that hardens the cell walls of plants. Lignin makes up most of what we call wood.

limiting factor
An environmental factor that restricts the number of individuals that can occupy a particular habitat, thus holding population growth in check.

linkage map
A map of a chromosome showing the relative positions of genes.

linked genes
Genes located close enough together on a chromosome that they are usually inherited together.

lipid
An organic compound consisting mainly of carbon and hydrogen atoms linked by nonpolar convalent bonds and therefore mostly hydrophobic and insoluble in water. Lipids include fats, waxes, phospholipids, and steroids.

liver
The largest organ in the vertebrate body. The liver performs diverse functions, such as producing bile, preparing nitrogenous wastes for disposal, and detoxifying poisonous chemicals in the blood.

lobe-finned fish
A bony fish with strong, muscular fins supported by bones.

locus
(plural, **loci**) The particular site where a gene is found on a chromosome. Homologous chromosomes have corresponding gene loci.

logistic population growth
A model that describes population growth that decreases as population size approaches carrying capacity.

loose connective tissue
The most widespread connective tissue in the vertebrate body. It binds epithelia to underlying tissues and functions as packing material, holding organs in place.

lung
An internal sac, lined with moist epithelium, where gases are exchanged between inhaled air and the blood.

lymph
A fluid similar to interstitial fluid that circulates in the lymphatic system.

lymph node
A small organ that is located along a lymph vessel and that filters lymph.

lymphatic system (*lim-fat′-ik*)
The organ system through which lymph circulates; includes lymph vessels, lymph nodes, and several other organs. The lymphatic system helps remove toxins and pathogens from the blood and interstitial fluid and returns fluid and solutes from the interstitial fluid to the circulatory system.

lymphocyte (*lim′-fuh-sīt*)
A type of white blood cell that carries out adaptive defenses—recognizing and responding to specific invading pathogens. There are two types of lymphocytes: B cells and T cells. *See also* B cell; T cell.

lysogenic cycle (*lī-sō-jen′-ik*)
A bacteriophage reproductive cycle in which the viral genome is incorporated into the bacterial host chromosome as a prophage. New phages are not produced, and the host cell is not killed or lysed unless the viral genome leaves the host chromosome.

lysosome (*lī′-sō-sōm*)
A digestive organelle in eukaryotic cells; contains enzymes that digest the cell's food and wastes.

lytic cycle (*lit′-ik*)
A viral reproductive cycle resulting in the release of new viruses by lysis (breaking open) of the host cell.

M

macroevolution
Evolutionary change above the species level, including the origin of evolutionary novelty and new taxonomic groups and the impact of mass extinctions on the diversity of life and its subsequent recovery.

macromolecule
A giant molecule formed by joining smaller molecules. Examples of macromolecules include proteins, polysaccharides, and nucleic acids.

macronutrient
A chemical element that an organism must obtain in relatively large amounts. *See also* micronutrient.

magnification
An increase in the apparent size of an object.

major depression
Depressive mental illness characterized by persistent sadness and loss of interest in pleasurable activities.

malignant tumor
An abnormal tissue mass that spreads into neighboring tissue and to other parts of the body; a cancerous tumor.

malnutrition
The absence of one or more essential nutrients from the diet.

mammal
Member of a class of endothermic amniotes that possesses mammary glands and hair.

mantle
In molluscs, the outgrowth of the body surface that drapes over the animal. The mantle produces the shell and forms the mantle cavity.

marsupial (*mar-sū′-pē-ul*)
A pouched mammal, such as a kangaroo, opossum, or koala. Marsupials give birth to embryonic offspring that complete development while housed in a pouch and attached to nipples on the mother's abdomen.

mass
A measure of the amount of material in an object.

mass number
The sum of the number of protons and neutrons in an atom's nucleus.

matrix
The thick fluid contained within the inner membrane of the mitochondrion.

matter
Anything that occupies space and has mass.

mechanoreceptor (*mek′-uh-nō-ri-sep′-ter*)
A sensory receptor that detects physical changes in the environment, associated with pressure, touch, stretch, motion, and sound.

medulla oblongata (*meh-duh′-luh ob′-long-got′-uh*)
Part of the vertebrate hindbrain continuous with the spinal cord; passes data between the spinal cord and forebrain and controls autonomic, homeostatic functions, including breathing, heart rate, swallowing, and digestion.

medusa (*med-ū′-suh*)
(plural, **medusae**) One of two types of cnidarian body forms; a floating, umbrella-like body form; also called a jelly.

meiosis (*mī-ō′-sis*)
In a sexually reproducing organism, the process of cell division that produces haploid gametes from diploid cells within the reproductive organs.

memory cell
A long-lived lymphocyte that responds to subsequent exposures to a specific pathogen. A memory cell is formed during the primary immune response and is activated by exposure to the same antigen that triggered its formation. When activated, a memory cell forms large clones of effector cells and memory cells that mount the secondary immune response.

meninges (*muh-nin′-jēz*)
Layers of connective tissue that enwrap and protect the brain and spinal cord.

menstrual cycle (*men′-strū-ul*)
The hormonally synchronized cyclic buildup and breakdown of the endometrium in some primates, including humans.

menstruation (*men′-strū-ā′-shun*)
Uterine bleeding resulting from the breakdown of the endometrium during a menstrual cycle.

meristem (*mār′-eh-stem*)
Plant tissue consisting of undifferentiated cells that divide and generate new cells and tissues.

mesophyll (*mes′-ō-fil*)
The green tissue in the interior of a leaf; a leaf's ground tissue system, the main site of photosynthesis.

messenger RNA (mRNA)
The type of ribonucleic acid that encodes genetic information from DNA and conveys it to ribosomes, where the information is translated into amino acid sequences.

metabolic rate
Energy expended by the body per unit time.

metabolism (*muh-tab′-uh-liz-um*)
The total of all the chemical reactions in an organism.

metamorphosis (*met′-uh-mōr′-fuh-sis*)
The transformation of a larva into an adult.

metaphase (*met′-eh-fāz*)
The second stage of mitosis. During metaphase, the centromeres of all the cell's duplicated chromosomes are lined up on an imaginary plate equidistant between the poles of the mitotic spindle.

metastasis (*muh-tas′-tuh-sis*)
The spread of cancer cells beyond their original site.

microevolution
A change in a population's gene pool over a succession of generations; evolutionary changes in species over relatively brief periods of geologic time.

micronutrient
A chemical element that an organism needs in very small amounts. *See also* macronutrient.

microtubule
The thickest of the three main kinds of fibers making up the cytoskeleton of a eukaryotic cell; a straight, hollow tube made of globular proteins called tubulins. Microtubules form the basis of the structure and movement of cilia and flagella.

middle ear
One of three main regions of the human ear; a chamber containing three small bones (the hammer, anvil, and stirrup) that convey vibrations from the eardrum to the inner ear.

millipede
A terrestrial arthropod that has two pairs of short legs for each of its numerous body segments and that eats decaying plant matter.

mineral
In nutrition, an inorganic chemical element (other than carbon, hydrogen, oxygen, or nitrogen) that an organism requires for proper body functioning.

mitochondrion (*mī′-tō-kon′-drē-on*)
(plural, **mitochondria**) An organelle in eukaryotic cells where cellular respiration occurs. Enclosed by two concentric membranes, it is where most of the cell's ATP is made.

mitosis (*mī′-tō-sis*)
The division of a single nucleus into two genetically identical daughter nuclei. Mitosis and cytokinesis make up the mitotic (M) phase of the cell cycle.

mitotic (M) phase
The phase of the cell cycle when mitosis divides the nucleus and distributes its chromosomes to the daughter nuclei and cytokinesis divides the cytoplasm, producing two daughter cells.

mitotic spindle
A spindle-shaped structure formed of microtubules and associated proteins that is involved in the movement of chromosomes during mitosis and meiosis. (A spindle is shaped roughly like a football.)

modern synthesis
A comprehensive theory of evolution that incorporates genetics and includes most of Darwin's ideas, focusing on populations as the fundamental units of evolution.

molecular biology
The study of the molecular basis of heredity; molecular genetics.

molecule
A group of two or more atoms held together by covalent bonds.

mollusc (*mol′-lusk*)
A soft-bodied animal characterized by a muscular foot, mantle, mantle cavity, and radula. Molluscs include gastropods (snails and slugs), bivalves (clams, oysters, and scallops), and cephalopods (squids and octopuses).

monocot (*mon′-uh-kot*)
A flowering plant whose embryos have a single seed leaf, or cotyledon.

monohybrid cross
A mating of individuals differing at one genetic locus.

monomer (*mon′-uh-mer*)
A chemical subunit that serves as a building block of a polymer.

monosaccharide (*mon′-uh-sak′-uh-rīd*)
The smallest kind of sugar molecule; a single-unit sugar; also known as a

simple sugar. Monosaccharides are the building blocks of more complex sugars and polysaccharides.

monotreme (*mon′-uh-trēm*)
An egg-laying mammal, such as the duck-billed platypus.

morning-after pill (MAP)
A birth control pill taken within three days of unprotected intercourse to prevent fertilization or implantation.

moss
Any of a group of seedless nonvascular plants.

motor neuron
A nerve cell that conveys command signals from the central nervous system to effector cells, such as muscle cells or gland cells.

motor output
The conduction of signals from the central nervous system to effector cells.

motor system
A component of the peripheral nervous system of vertebrates composed of neurons that carry signals to skeletal muscles, mainly in response to external stimuli. The motor system is primarily under voluntary control.

motor unit
A motor neuron and all the muscle fibers it controls.

mouth
See oral cavity.

movement corridor
A series of small clumps or a narrow strip of quality habitat (usable by organisms) that connects otherwise isolated patches of quality habitat.

muscle tissue
Tissue consisting of long muscle cells that are capable of contracting when stimulated by nerve impulses. *See also* skeletal muscle; cardiac muscle; smooth muscle.

muscular system
All the skeletal muscles in the body. (Cardiac muscle and smooth muscle are components of other organ systems.)

mutagen (*myū′-tuh-jen*)
A chemical or physical agent that interacts with DNA and causes a mutation.

mutation
A change in the nucleotide sequence of DNA; a major source of genetic diversity.

mutualism
An interspecific interaction in which both partners benefit.

mycelium (*mī-sē′-lē-um*)
(plural, **mycelia**) The densely branched network of hyphae in a fungus.

mycorrhiza (*mī′-kō-rī′-zuh*)
(plural, **mycorrhizae**) A mutually beneficial symbiotic association of a plant root and fungus.

myelin sheath (*mī′-uh-lin*)
A chain of bead-like supporting cells that insulate the axon of a nerve cell in vertebrates. This insulation helps to speed electrical transmission along the axon.

myofibril (*mī′-ō-fī′-bril*)
A contractile unit in a muscle cell (fiber) made up of many arcomeres. Longitudinal bundles of myofibrils make up a muscle fiber.

N

NADH
An electron carrier (a molecule that carries electrons) involved in cellular respiration and photosynthesis. NADH carries electrons from glucose and other fuel molecules and deposits them at the top of an electron transport chain. NADH is generated during glycolysis and the citric acid cycle.

NADPH
An electron carrier (a molecule that carries electrons) involved in photosynthesis. Light drives electrons from chlorophyll to $NADP^+$, forming NADPH, which provides the high-energy electrons for the reduction of carbon dioxide to sugar in the Calvin cycle.

natural family planning
See rhythm method.

natural killer (NK) cell
A white blood cell that attacks cancer cells and infected body cells as part of internal innate defense.

natural selection
A process in which organisms with certain inherited characteristics are more likely to survive and reproduce than are organisms with other characteristics; unequal reproductive success.

nearsightedness
An inability to focus on distant objects; occurs when the eyeball is longer than normal and the lens focuses distant objects in front of the retina; also called myopia.

negative feedback
A control mechanism in which a chemical reaction, metabolic pathway, or hormone-secreting gland is inhibited by the products of the reaction, pathway, or gland. As the concentration of the products builds up, the product molecules themselves inhibit the process that produced them.

negative pressure breathing
A breathing system in which lower air pressure in the lungs causes air to enter the lungs.

nematode (*nem′-uh-tōd*)
An animal characterized by a pseudocoelom, a cylindrical, wormlike body form, and a complete digestive tract; also called a roundworm.

nephron
The tubular excretory unit and associated blood vessels of the vertebrate kidney. The nephron extracts filtrate from the blood and refines it into urine.

nerve
A communication line made up of cable-like bundles of neuron fibers (axons and dendrites) tightly wrapped in connective tissue.

nervous system
The organ system that forms a communication and coordination network throughout an animal's body.

nervous tissue
Tissue made up of neurons and supportive cells.

neuron (*nūr′-on*)
A nerve cell; the fundamental structural and functional unit of the nervous system, specialized for carrying signals from one location in the body to another.

neurotransmitter
A chemical messenger that carries information from a transmitting neuron to a receiving cell, either another neuron or an effector cell.

neutron
An electrically neutral particle (a particle having no electrical charge), found in the nucleus of an atom.

nitrogen fixation
The conversion of atmospheric nitrogen (N_2) to nitrogen compounds (NH_4, NO_3) that plants can absorb and use.

node
The point of attachment of a leaf on a stem.

nondisjunction
An accident of meiosis or mitosis in which a pair of homologous chromosomes or a pair of sister chromatids fail to separate at anaphase.

norepinephrine (*nor′-ep-uh-nef′-rin*)
An amine hormone (also called noradrenaline) that is secreted by the adrenal medulla and that prepares body organs for "fight or flight"; also serves as a neurotransmitter.

notochord (*nō′-tuh-kord*)
A flexible, cartilage-like, longitudinal rod located between the digestive tract and nerve cord in chordate animals, present only in embryos in many species.

nuclear envelope
A double membrane, perforated with pores, that encloses the nucleus and separates it from the rest of the eukaryotic cell.

nuclear transplantation
A technique in which the nucleus of one cell is placed into another cell that already has a nucleus or in which the nucleus has been previously destroyed. The cell is then stimulated to grow, producing an embryo that is a genetic copy of the nucleus donor.

nucleic acid (*nū-klā′-ik*)
A polymer consisting of many nucleotide monomers; serves as a blueprint for proteins and, through the actions of proteins, for all cellular structures and activities. The two types of nucleic acids are DNA and RNA.

nucleic acid probe (*nū-klā′-ik*)
In DNA technology, a labeled single-stranded nucleic acid molecule used to find a specific gene or other nucleotide sequence within a mass of

DNA. The probe hydrogen-bonds to the complementary sequence in the targeted DNA.

nucleoid
A non–membrane-enclosed region in a prokaryotic cell where the DNA is concentrated.

nucleolus (*nū-klē′-ō-lus*)
A structure within the nucleus of a eukaryotic cell where ribosomal RNA is made and assembled with proteins to make ribosomal subunits; consists of parts of the chromatin DNA, RNA transcribed from the DNA, and proteins imported from the cytoplasm.

nucleosome (*nū′-klē-ō-sōm*)
The bead-like unit of DNA packing in a eukaryotic cell; consists of DNA wound around a protein core made up of eight histone molecules.

nucleotide (*nū′-klē-ō-tīd*)
An organic monomer consisting of a five-carbon sugar covalently bonded to a nitrogenous base and a phosphate group. Nucleotides are the building blocks of nucleic acids.

nucleus
(plural, **nuclei**) (1) An atom's central core, containing protons and neutrons. (2) The genetic control center of a eukaryotic cell.

O

obesity
An excessively high body mass index, a ratio of weight to height.

omnivore
An animal that eats both plants and animals. *See also* carnivore; herbivore.

oncogene (*on′-kō-jēn*)
A cancer-causing gene; usually contributes to malignancy by abnormally enhancing the amount or activity of a growth factor made by the cell.

oogenesis (*ō′-uh-jen′-uh-sis*)
The formation of egg cells within the ovaries.

open circulatory system
A circulatory system in which the circulating fluid is pumped through open-ended vessels and out among the body cells. In an animal with an open circulatory system, the circulating fluid and interstitial fluid are the same.

open system
Any system that exchanges chemicals and energy with its surroundings. All organisms are open systems.

operator
In prokaryotic DNA, a sequence of nucleotides near the start of an operon to which an active repressor can attach. The binding of repressor prevents RNA polymerase from attaching to the promoter and transcribing the genes of the operon.

operculum (*ō-per′-kyū-lum*)
(plural, **opercula**) A protective flap on each side of a bony fish's head that covers a chamber housing the gills.

operon (*op′-er-on*)
A unit of genetic regulation common in prokaryotes; a cluster of genes with related functions, along with the promoter and operator that control their transcription.

opportunistic life history
The pattern of reproducing when young and producing many offspring that receive little or no parental care; often seen in short-lived, small-bodied species.

optic nerve
A nerve that arises from the retina in each eye and carries visual information to the brain.

oral cavity
An opening through which food is taken into an animal's body; also known as the mouth.

order
In classification, the taxonomic category above family.

organ
A structure consisting of two or more tissues that coordinate to perform specific functions.

organ system
A group of organs that work together in performing vital body functions.

organelle (*ōr-guh-nel′*)
A membrane-enclosed structure with a specialized function within a eukaryotic cell.

organic compound
A chemical compound containing the element carbon and usually synthesized by cells.

organic farming
A method of farming intended to promote environmental sustainability through such practices as crop rotation, water conservation, and avoidance of synthetic fertilizers, pesticides, and genetically modified organisms.

organism
An individual living thing, such as a bacterium, fungus, protist, plant, or animal.

organismal ecology
The study of the evolutionary adaptations that enable individual organisms to meet the challenges posed by their abiotic environments.

osmoconformer (*oz′-mō-con-form′-er*)
An organism whose body fluids have a solute concentration equal to that of its surroundings. Osmoconformers do not have a net gain or loss of water by osmosis.

osmoregulation
The control of the gain or loss of water and dissolved solutes in an organism.

osmoregulator
An organism whose body fluids have a solute concentration different from that of its environment and that must use energy in controlling water loss or gain.

osmosis (*oz-mō′-sis*)
The diffusion of water across a selectively permeable membrane.

osteoporosis (*os′-tē -ō-puh-rō′-sis*)
A skeletal disorder characterized by thinning, porous, and easily broken bones. Osteoporosis is common among women after menopause and is often related to low estrogen levels.

outer ear
One of three main regions of the ear in humans and some other animals. The outer ear is made up of the auditory canal and the pinna.

ovarian cycle (*ō-vār′-ē-un*)
Hormonally synchronized cyclic events in the mammalian ovary, culminating in ovulation.

ovary
(1) In animals, the female gonad, which produces egg cells and reproductive hormones. (2) In flowering plants, the base of a carpel in which the egg-containing ovules develop.

oviduct (*ō′-vuh-dukt*)
The tube that conveys egg cells away from an ovary; also called a fallopian tube.

ovulation (*ah′-vyū-lā′-shun*)
The release of an egg cell from an ovarian follicle.

ovule (*ō′-vyūl*)
In a seed plant, a reproductive structure that contains the female gametophyte and the developing egg. An ovule develops into a seed.

oxidation
The loss of electrons from a substance involved in a redox reaction; always accompanies reduction.

P

P generation
The parent individuals from which offspring are derived in studies of inheritance. P stands for parental.

pacemaker
The SA (sinoatrial) node; a region of cardiac muscle that maintains the heart's pumping rhythm (heartbeat) by setting the rate at which the heart contracts.

paedomorphosis (*pē′-duh-mōr′-fuh-sis*)
The retention in the adult of features that were juvenile in ancestral species.

pain receptor
A sensory receptor that detects painful stimuli.

pancreas (*pan′-krē-us*)
A gland with dual functions: The nonendocrine portion secretes digestive enzymes and an alkaline solution into the small intestine via a duct; the endocrine portion secretes the hormones insulin and glucagon into the blood.

parasite
An organism that lives in or on another organism (the host) from which it obtains nourishment; an organism that benefits at the expense of another organism, which is harmed in the process.

parasympathetic division
One of two sets of neurons in the autonomic nervous system; generally promotes body activities that gain and conserve energy ("rest

and digest"). *See also* sympathetic division.

parathyroid gland (*pār′-uh-thī′-royd*)
One of four endocrine glands embedded in the surface of the thyroid gland that secrete parathyroid hormone; functions in calcium homeostasis.

parathyroid hormone (PTH)
A peptide hormone, secreted by the parathyroid glands, that raises blood calcium level.

parenchyma cell (*puh-reng′-kuh-muh*)
In plants, an abundant and relatively unspecialized type of cell with a thin primary wall and no secondary wall; functions in photosynthesis, food storage, and aerobic respiration and may differentiate into other cell types.

passive transport
The diffusion of a substance across a biological membrane without any input of energy.

pathogen
A disease-causing virus or organism.

pedigree
A family tree representing the occurrence of heritable traits in parents and offspring across a number of generations.

pelagic realm (*puh-laj′-ik*)
The open-water region of an ocean.

penis
The structure in male mammals that functions in sexual intercourse.

pepsin
An enzyme present in gastric juice that begins the hydrolysis of proteins.

peptide bond
The covalent linkage between two amino acid units in a polypeptide, formed by a dehydration reaction between two amino acids.

perennial (*puh-ren′-ē-ul*)
A plant that lives for many years.

peripheral nervous system (PNS)
The network of nerves carrying signals into and out of the central nervous system.

peristalsis (*par′-uh-stal′-sis*)
Rhythmic waves of contraction of smooth muscles. Peristalsis propels food through a digestive tube and also enables many animals, such as earthworms, to crawl.

permafrost
Continuously frozen subsoil found in the arctic tundra.

petal
A modified leaf of a flowering plant. Petals are the often colorful parts of a flower that advertise it to insects and other pollinators.

petiole (*pet′-ē-ōl*)
The stalk of a leaf, which joins the leaf to a node of the stem.

pH scale
A measure of the relative acidity of a solution, ranging in value from 0 (most acidic) to 14 (most basic). pH stands for potential hydrogen and refers to the concentration of hydrogen ions (H^+).

phage (*fāj*)
See bacteriophage.

phagocytic cell (*fag′-ō-si-tik*)
A white blood cell that engulfs bacteria, foreign proteins, and the remains of dead body cells as part of internal innate defense.

phagocytosis (*fag′-ō-sī-tō′-sis*)
Cellular "eating"; a type of endocytosis whereby a cell engulfs large molecules, other cells, or particles into its cytoplasm.

pharyngeal slit (*fuh-rin′-jē-ul*)
A gill structure in the pharynx, found in chordate embryos and some adult chordates.

pharynx (*far′-inks*)
The organ in a digestive tract that receives food from the oral cavity; in terrestrial vertebrates, the throat region where the air and food passages cross.

phenotype (*fē′-nō-tīp*)
The expressed traits of an organism.

phloem (*flō′-um*)
The portion of a plant's vascular system that conveys sugars, nutrients, and hormones throughout a plant. Phloem is made up of live food-conducting cells.

phloem sap
The solution of sugars, other nutrients, and hormones conveyed throughout a plant via phloem tissue.

phospholipid (*fos′-fō-lip′-id*)
A molecule that is a constituent of the inner bilayer of biological membranes, having a hydrophilic head and a hydrophobic tail.

phospholipid bilayer
A double layer of phospholipid molecules (each molecule consisting of a phosphate group bonded to two fatty acids) that is the primary component of all cellular membranes.

photic zone (*fō′-tik*)
Shallow water near shore or the upper layer of water away from the shore; region of an aquatic ecosystem where sufficient light is available for photosynthesis.

photon (*fō′-ton*)
A fixed quantity of light energy. The shorter the wavelength of light, the greater the energy of a photon.

photoperiod
The length of the day relative to the length of the night; an environmental stimulus that plants use to detect the time of year.

photoreceptor
A type of electromagnetic receptor that detects light.

photosynthesis (*fō′-tō-sin′-thuh-sis*)
The process by which plants, algae, and some bacteria transform light energy to chemical energy stored in the bonds of sugars. This process requires an input of carbon dioxide (CO_2) and water (H_2O) and produces oxygen gas (O_2) as a waste product.

photosystem
A light-harvesting unit of a chloroplast's thylakoid membrane; consists of several hundred molecules, a reaction-center chlorophyll, and a primary electron acceptor.

phototropism (*fō′-tō-trō′-pizm*)
The directional growth of a plant shoot in response to light.

phylogenetic tree (*fī′-lō-juh-net′-ik*)
A branching diagram that represents a hypothesis about evolutionary relationships between organisms.

phylum (*fī′-lum*)
(plural, **phyla**) In classification, the taxonomic category above class and below kingdom. Members of a phylum all have a similar general body plan.

physiology (*fi′-zē-ol′-uh-jē*)
The study of the function of an organism's structural equipment.

phytoplankton (*fī′-tō-plank′-ton*)
Algae and photosynthetic bacteria that drift passively in aquatic environments.

pinna (*pin′-uh*)
The flap-like part of the outer ear in humans and some other animals. The pinna collects sound waves and channels them to the auditory canal.

pith
Part of the ground tissue system of a eudicot plant. Pith fills the center of a stem and may store food.

pituitary gland (*puh-tū′-uh-tār′-ē*)
An endocrine gland at the base of the hypothalamus; consists of a posterior lobe, which stores and releases two hormones produced by the hypothalamus, and an anterior lobe, which produces and secretes many hormones that regulate diverse body functions.

pivot joint
A joint that allows precise rotations in multiple planes. An example in humans is the elbow.

placenta (*pluh-sen′-tuh*)
In most mammals, the organ that provides nutrients and oxygen to the embryo and helps dispose of its metabolic wastes. The placenta is formed of the embryo's chorion and the mother's endometrial blood vessels.

placental mammal (*pluh-sen′-tul*)
Mammal whose young complete their embryonic development in the uterus, nourished via the mother's blood vessels in the placenta; also called a eutherian.

plankton
Communities of organisms, mostly microscopic, that drift passively in ponds, lakes, and oceans.

plant
A multicellular eukaryote that carries out photosynthesis and has a set of structural and reproductive terrestrial adaptations, including a multicellular, dependent embryo.

plasma
The yellowish liquid of the blood in which the blood cells are suspended.

plasma membrane
The thin layer of lipids and proteins that sets a cell off from its surroundings and acts as a selective barrier to the passage of ions and molecules into and out of the cell; consists of a phospholipid bilayer in which proteins are embedded.

plasmid
A small ring of self-replicating DNA separate from the chromosome(s). Plasmids are found in prokaryotes and yeasts.

plasmodial slime mold (*plaz-mō′-dē-ul*)
A type of protist named for an amoeboid plasmodial feeding stage in its life cycle.

platelet
A piece of cytoplasm from a large cell in the bone marrow; a blood-clotting element.

pleiotropy (*plī′-uh-trō-pē*)
The control of more than one phenotypic character by a single gene.

polar ice
A terrestrial biome that includes regions of extremely cold temperature and low precipitation located at high latitudes north of the arctic tundra and in Antarctica.

polar molecule
A molecule containing an uneven distribution of charge due to the presence of polar covalent bonds (bonds having opposite charges on opposite ends).

pollen grain
In a seed plant, the male gametophyte that develops within the anther of a stamen. It houses cells that will develop into sperm.

pollination
In seed plants, the delivery, by wind or animals, of pollen from the male parts of a plant to the stigma of a carpel on the female.

polychaete
A type of annelid, or segmented worm, that typically lives on the seafloor.

polygenic inheritance (*pol′-ē-jen′-ik*)
The additive effect of two or more genes on a single phenotypic characteristic.

polymer (*pol′-uh-mer*)
A large molecule consisting of many identical or similar molecular units, called monomers, covalently joined together in a chain.

polymerase chain reaction (PCR) (*puh-lim′-uh-rās*)
A technique used to obtain many copies of a DNA molecule or many copies of part of a DNA molecule. A small amount of DNA mixed with the enzyme DNA polymerase, DNA nucleotides, and a few other ingredients replicates repeatedly in a test tube.

polynucleotide (*pol′-ē-nū′-klē-ō-tīd*)
A polymer made up of many nucleotides covalently bonded together.

polyp (*pol′-ip*)
One of two types of cnidarian body forms; a stationary (sedentary), columnar, hydra-like body.

polypeptide
A chain of amino acids linked by peptide bonds.

polysaccharide (*pol′-ē-sak′-uh-rīd*)
A carbohydrate polymer consisting of many monosaccharides (sugars) linked by covalent bonds.

population
A group of interacting individuals belonging to one species and living in the same geographic area at the same time.

population density
The number of individuals of a species per unit area or volume of the habitat.

population ecology
The study of how members of a population interact with their environment, focusing on factors that influence population density and growth.

population momentum
In a population in which the fertility rate averages two children per female (replacement rate), the continuation of population growth as girls reach their reproductive years.

positive feedback
A control mechanism in which the products of a process stimulate the process that produced them.

post-anal tail
A tail posterior to the anus, found in chordate embryos and most adult chordates.

posterior pituitary
An extension of the hypothalamus composed of nervous tissue that secretes hormones made in the hypothalamus; a temporary storage site for hypothalamic hormones.

postzygotic barrier (*pōst′-zī-got′-ik*)
A reproductive barrier that operates if interspecies mating occurs and forms hybrid zygotes.

potential energy
Stored energy; the energy that an object has due to its location and/or arrangement. Water behind a dam and chemical bonds both possess potential energy.

predation
An interaction between species in which one species, the predator, kills and eats the other, the prey.

prepuce (*prē′-pyūs*)
A fold of skin covering the head of the clitoris or penis.

pressure-flow mechanism
The method by which phloem sap is transported through a plant from a sugar source, where sugars are produced, to a sugar sink, where sugars are used. The mechanism relies on building up water pressure at the source end of the phloem tube and reducing water pressure at the sink end.

prezygotic barrier (*prē′-zī-got′-ik*)
A reproductive barrier that impedes mating between species or hinders fertilization of eggs if members of different species attempt to mate.

primary consumer
An organism that eats only autotrophs; an herbivore.

primary electron acceptor
A molecule in the reaction center of a photosystem that traps the light-excited electron from the reaction-center chlorophyll.

primary growth
Growth in the length of a plant root or shoot produced by an apical meristem.

primary immune response
The initial immune response to an antigen, which includes production of effector cells that respond to the antigen within a few days and also memory cells that will respond to future exposure to the antigen.

primary oocyte (*ō′-uh-sīt*)
A diploid cell, in prophase I of meiosis, that can be hormonally triggered to develop into an ovum.

primary production
The amount of solar energy converted to chemical energy (organic compounds) by autotrophs in an ecosystem during a given time period.

primary spermatocyte (*sper-mat′-eh-sīt′*)
A diploid cell in the testis that undergoes meiosis I.

primary structure
The first level of protein structure; the specific sequence of amino acids making up a polypeptide chain.

primary succession
A type of ecological succession in which a biological community begins in an area without soil. *See also* secondary succession.

primate
Member of the mammalian group that includes lorises, pottos, lemurs, tarsiers, monkeys, apes, and humans.

prion
An infectious form of protein that may multiply by converting related proteins to more prions. Prions cause several related diseases in different animals, including scrapie in sheep, mad cow disease, and Creutzfeldt-Jakob disease in humans.

producer
An organism that makes organic food molecules from carbon dioxide, water, and other inorganic raw materials: a plant, alga, or autotrophic bacterium; the trophic level that supports all others in a food chain or food web.

product
An ending material in a chemical reaction.

progestin (*prō-jes′-tin*)
One of a family of sex hormones, including progesterone, produced by the mammalian ovary. Progestins prepare the uterus for pregnancy.

programmed cell death
The timely death (and disposal of the remains) of certain cells, triggered by certain genes; an essential process in normal development.

prokaryote (*prō-kār′-ē-ōt*)
An organism characterized by prokaryotic cells. *See also* prokaryotic cell.

prokaryotic cell (*prō-kār′-ē-ot′-ik*)
A type of cell lacking a nucleus and other organelles. Prokaryotic cells are found only in the domains Bacteria and Archaea.

promoter
A specific nucleotide sequence in DNA, located at the start of a gene,

that is the binding site for RNA polymerase and the place where transcription begins.

prophage (*prō′-fāj*)
Phage DNA that has inserted into the DNA of a prokaryotic chromosome.

prophase
The first stage of mitosis. During prophase, duplicated chromosomes condense to form structures visible with a light microscope, and the mitotic spindle forms and begins moving the chromosomes toward the center of the cell.

prostate gland (*pros′-tāt*)
A gland in human males that secretes an acid-neutralizing component of semen.

protein
A biological polymer constructed from amino acid monomers.

proteomics
The systematic study of the full protein sets (proteomes) encoded by genomes.

protist (*prō′-tist*)
Any eukaryote that is not a plant, animal, or fungus.

proton
A subatomic particle with a single unit of positive electrical charge, found in the nucleus of an atom.

proto-oncogene (*prō′-tō-on′-kō-jēn*)
A normal gene that can be converted to a cancer-causing gene.

protozoan (*prō′-tō-zō′-un*)
A protist that lives primarily by ingesting food; a heterotrophic, animal-like protist.

provirus
Viral DNA that inserts into a host genome.

pseudocoelom (*sū′-dō-sē′-lōm*)
A body cavity that is not completely lined by tissue derived from mesoderm.

pseudopodium (*sū′-dō-pō′-dē-um*)
(plural, **pseudopodia**) A temporary extension of an amoeboid cell. Pseudopodia function in moving cells and engulfing food.

pulmonary circuit
One of two main blood circuits in terrestrial vertebrates; conveys blood between the heart and the lungs. *See also* systemic circuit.

pulse
The rhythmic stretching of the arteries caused by the pressure of blood forced through the arteries by contractions of the ventricles during systole.

punctuated equilibria
In the fossil record, long periods of little apparent change (equilibria) interrupted (punctuated) by relatively brief periods of sudden change.

Punnett square
A diagram used in the study of inheritance to show the results of random fertilization.

pupil
The opening in the iris that admits light into the interior of the vertebrate eye. Muscles in the iris regulate its size.

pyramid of production
A diagram depicting the cumulative loss of energy with each transfer in a food chain.

Q

quaternary consumer (*kwot′-er-nār-ē*)
An organism that eats tertiary consumers.

R

radial symmetry
An arrangement of the body parts of an organism like pieces of a pie around an imaginary central axis. Any slice passing longitudinally through a radially symmetric organism's central axis divides the organism into mirror-image halves.

radiation therapy
Treatment for cancer in which parts of the body that have cancerous tumors are exposed to high-energy radiation to disrupt cell division of the cancer cells.

radioactive isotope
An isotope whose nucleus decays spontaneously, giving off particles and energy.

radiometric dating
A method for determining the age of fossils and rocks from the ratio of a radioactive isotope to the nonradioactive isotope(s) of the same element in the sample.

radula (*rad′-yū-luh*)
A file-like organ found in many molluscs, used to scrape up or shred food.

ray-finned fish
A bony fish having fins supported by thin, flexible skeletal rays. All but one living species of bony fishes are ray-fins. *See* lobe-finned fish.

reabsorption
In the vertebrate kidney, the reclaiming of water and valuable solutes from the filtrate.

reactant
A starting material in a chemical reaction.

reaction center
In a photosystem in a chloroplast, the chlorophyll *a* molecule and primary electron acceptor that trigger the light reactions of photosynthesis. The chlorophyll donates an electron excited by light energy to the primary electron acceptor, which passes an electron to an electron transport chain.

receptor potential
The change in membrane potential of a sensory receptor cell that results from sensory transduction.

recessive allele
In heterozygotes, the allele that has no noticeable effect on the phenotype.

recombinant DNA
A DNA molecule carrying genes derived from two or more sources, often from different species.

recombination frequency
With respect to two given genes, the number of recombinant progeny from a mating divided by the total number of progeny. Recombinant progeny carry combinations of alleles different from that seen in either of the parents as a result of independent assortment of chromosomes and crossing over.

rectum
The terminal portion of the large intestine, where the feces are stored until they are eliminated.

red blood cell
A blood cell containing hemoglobin, which transports O_2; also called an erythrocyte.

red-green colorblindness
A common sex-linked human disorder involving several genes on the X chromosome and characterized by a malfunction of light-sensitive cells in the eyes; affects mostly males but also homozygous females.

redox reaction
Short for reduction-oxidation reaction; a chemical reaction in which electrons are lost from one substance (oxidation) and added to another (reduction). Oxidation and reduction always occur together.

reduction
The gain of electrons by a substance involved in a redox reaction; always accompanies oxidation.

regeneration
The regrowth of body parts from pieces of an organism.

relative abundance
The proportional representation of a species in a biological community; one component of species diversity.

relative fitness
The contribution an individual makes to the gene pool of the next generation relative to the contribution of other individuals in the population.

repetitive DNA
Nucleotide sequences that are present in many copies in the DNA of a genome. The repeated sequences may be long or short and may be located next to each other or dispersed in the DNA.

repressor
A protein that blocks the transcription of a gene or operon.

reproduction
The creation of new individuals from existing ones.

reproductive barrier
Anything that prevents individuals of closely related species from interbreeding, even when populations of the two species live together.

reproductive cloning
Using a somatic cell from a multicellular organism to make one or more genetically identical individuals.

reproductive cycle
In females, a recurring series of events that produces gametes, makes

them available for fertilization, and prepares the body for pregnancy.

reptile
Member of the clade of amniotes that includes snakes, lizards, turtles, crocodiles, alligators, birds, and a number of extinct groups (most of the dinosaurs).

resolving power
A measure of the clarity of an image; the ability of an optical instrument to show two objects as separate.

respiratory surface
The part of an animal where gases are exchanged with the environment.

respiratory system
The organ system that functions in exchanging gases with the environment, taking in O_2 and disposing of CO_2.

resting potential
The voltage across the plasma membrane of a resting neuron.

restoration ecology
A field of ecology that develops methods of returning degraded ecosystems to their natural state.

restriction enzyme
A bacterial enzyme that cuts up foreign DNA at one very specific nucleotide sequence, thus protecting bacteria against intruding DNA from phages and other organisms. Restriction enzymes are used in DNA technology to cut DNA molecules in reproducible ways.

restriction fragment
A molecule of DNA produced from a longer DNA molecule cut up by a restriction enzyme; used in genome mapping and other applications.

restriction site
A specific sequence on a DNA strand that is recognized and cut by a restriction enzyme.

retina (*ret′-uh-nuh*)
The light-sensitive layer in an eye, made up of photoreceptor cells and sensory neurons.

retrovirus
An RNA virus that reproduces by means of a DNA molecule. It reverse-transcribes its RNA into DNA, inserts the DNA into a cellular chromosome, and then transcribes more copies of the RNA from the viral DNA. HIV and a number of cancer-causing viruses are retroviruses.

reverse transcriptase (*tran-skrip′-tās*)
An enzyme that catalyzes the synthesis of DNA on an RNA template.

rheumatoid arthritis
An autoimmune disease in which the joints become highly inflamed.

rhizome (*rī′-zōm*)
A horizontal stem that grows below the ground.

rhythm method
A form of contraception that relies on refraining from sexual intercourse when conception is most likely to occur; also called natural family planning.

ribosomal RNA (rRNA) (*rī′-buh-sōm′-ul*)
The type of ribonucleic acid that, together with proteins, makes up ribosomes; the most abundant type of RNA.

ribosome (*rī′-buh-sōm*)
A cellular structure consisting of RNA and protein organized into two subunits and functioning as the site of protein synthesis in the cytoplasm. The ribosomal subunits are constructed in the nucleolus.

RNA
Ribonucleic acid (*rī′-bō-nū-klā′-ik*)
A type of nucleic acid consisting of nucleotide monomers, with a ribose sugar, a phosphate group, and the nitrogenous bases adenine (A), cytosine (C), guanine (G), and uracil (U); usually single-stranded; functions in protein synthesis and as the genome of some viruses.

RNA polymerase (*puh-lim′-uh-rās*)
An enzyme that links together the growing chain of RNA nucleotides during transcription, using a DNA strand as a template.

RNA splicing
The removal of introns and joining of exons in eukaryotic RNA, forming an mRNA molecule with a continuous coding sequence; occurs before mRNA leaves the nucleus.

rod
A photoreceptor cell in the vertebrate retina, enabling vision in dim light (but only in shades of gray).

root
The underground organ of a plant. Roots anchor the plant in the soil, absorb and transport minerals and water, and store food.

root cap
A cone of cells at the tip of a plant root that protects the root's apical meristem.

root hair
An outgrowth of an epidermal cell on a root, which increases the root's absorptive surface area.

root system
All of a plant's roots, which anchor it in the soil, absorb and transport minerals and water, and store food.

rough ER (rough endoplasmic reticulum) (*reh-tik′-yuh-lum*)
A network of interconnected membranous sacs in a eukaryotic cell's cytoplasm. Rough ER membranes are studded with ribosomes that make membrane proteins and secretory proteins. The rough ER constructs membrane from phospholipids and proteins.

roundworm
See nematode.

rule of multiplication
A rule stating that the probability of a compound event is the product of the separate probabilities of the independent events.

S

SA (sinoatrial) node (*sī′-nō-ā′-trē-ul*)
The pacemaker of the heart, located in the wall of the right atrium. At the base of the wall separating the two atria is another patch of nodal tissue called the atrioventricular (AV) node. *See also* pacemaker.

salivary gland
A gland associated with the oral cavity that secretes substances that lubricate food and begin the process of chemical digestion.

sarcomere (*sar′-kō-mēr*)
The fundamental unit of muscle contraction, composed of thin filaments and thick filaments; the region between two narrow, dark lines in the myofibril.

saturated
Pertaining to fats and fatty acids the hydrocarbon chains of which contain the maximum number of hydrogens and therefore have no double covalent bonds. Because of their straight, flat shape, saturated fats and fatty acids tend to be solid at room temperature.

savanna
A terrestrial biome dominated by grasses and scattered trees. Frequent fires and seasonal drought are significant abiotic factors.

scanning electron microscope (SEM)
A microscope that uses an electron beam to study the surface architecture of a cell or other specimen.

scavenger
An animal that feeds on the carcasses of dead animals.

science
Any method of learning about the natural world that follows the scientific method. *See* discovery science; hypothesis-driven science.

scientific method
Scientific investigation involving the observation of phenomena, the formulation of a hypothesis concerning the phenomena, experimentation to demonstrate the truth or falseness of the hypothesis, and results that validate or modify the hypothesis.

sclera (*sklār′-uh*)
A tough, whitish layer of connective tissue forming the outer surface of the vertebrate eye. The cornea is the front part of the sclera.

sclerenchyma cell (*skli-reng′-kuh-muh*)
In plants, a supportive type of cell with a rigid secondary wall hardened with lignin.

scrotum
A pouch of skin outside the abdomen that houses a testis. The scrotum functions in cooling the sperm, thereby keeping them viable.

seaweed
A large, multicellular marine alga.

secondary consumer
An organism that eats primary consumers.

secondary growth
An increase in a plant's girth, involving cell division in the vascular cambium and cork cambium.

secondary immune response
The immune response elicited by memory cells upon exposure to a previously encountered antigen. The

secondary immune response is more rapid, of greater magnitude, and of longer duration than the primary immune response.

secondary oocyte (*ō′-uh-sīt′*)
A haploid cell that results from meiosis I in oogenesis and that will become an ovum after meiosis II.

secondary spermatocyte (*sper-mat′-uh-sīt′*)
A haploid cell that results from meiosis I in spermatogenesis and that will become a sperm cell after meiosis II.

secondary succession
A type of ecological succession that occurs where a disturbance has destroyed an existing biological community but left the soil intact. *See also* primary succession.

secretion
In the vertebrate kidney, the transport of certain substances, such as some ions and drugs, from the blood into the filtrate.

seed
A plant embryo packaged with a food supply within a protective covering.

seed coat
A tough outer covering of a seed, formed from the outer coat of an ovule. In a flowering plant, it encloses and protects the embryo and endosperm.

semen (*sē′-mun*)
The sperm-containing fluid that is ejaculated by the male during orgasm.

seminal vesicle (*sem′-uh-nul ves′-uh-kul*)
A gland in males that secretes a fluid component of semen that lubricates and nourishes sperm.

seminiferous tubule (*sem′-uh-nif′-uh-rus*)
A coiled sperm-producing tube in a testis.

sensory adaptation
The tendency of some sensory receptors to become less sensitive when they are stimulated repeatedly.

sensory input
The conduction of signals from sensory receptors to integration centers in the central nervous system.

sensory neuron
A nerve cell that receives information from sensory receptors and conveys signals into the central nervous system.

sensory transduction
The conversion of a stimulus signal to an electrical signal by a sensory receptor cell.

sepal (*sē′-pul*)
A modified leaf of a flowering plant. A whorl of sepals encloses and protects the flower bud before it opens.

sex chromosome
A chromosome that determines whether an individual is male or female; in mammals, for example, the X or Y chromosome.

sex-linked gene
A gene located on a sex chromosome.

sexual dimorphism
Distinction in appearance based on secondary sexual characteristics, noticeable differences not directly associated with reproduction or survival.

sexual reproduction
The creation of genetically distinct offspring by the fusion of two haploid sex cells (gametes: sperm and egg), forming a diploid zygote.

sexual selection
A form of natural selection in which individuals with certain characteristics are more likely than other individuals to obtain mates.

sexually transmitted disease (STD)
A contagious disease spread by sexual contact.

shoot
The aerial organ of a plant, consisting of stem and leaves. Leaves are the main photosynthetic structures of most plants.

shoot system
All of a plant's stems, leaves, and reproductive structures.

short tandem repeat (STR)
DNA consisting of tandem (in a row) repeats of a short sequence of nucleotides.

sickle-cell disease
A genetic disorder in which the red blood cells have abnormal hemoglobin molecules and take on an abnormal shape.

signal transduction pathway
A series of molecular changes that converts a signal received on a target cell's surface to a specific response inside the cell.

silencer
A eukaryotic DNA sequence that inhibits the start of gene transcription; may act analogously to an enhancer, binding a repressor.

sister chromatid (*krō′-muh-tid*)
One of the two identical parts of a duplicated chromosome. While joined, two sister chromatids make up one chromosome; chromatids are eventually separated during mitosis or meiosis II.

skeletal muscle
Striated muscle attached to the skeleton. The contraction of striated muscle produces voluntary movements of the body.

skeletal system
The organ system that provides body support, protects body organs such as the brain, heart, and lungs, and anchors the muscles.

small intestine
The longest section of the alimentary canal. It is the principal site of the enzymatic hydrolysis of food molecules and absorption of nutrients.

smooth ER (smooth endoplasmic reticulum) (*reh-tik′-yuh-lum*)
A network of interconnected membranous tubules in a eukaryotic cell's cytoplasm. Smooth ER lacks ribosomes. Enzymes embedded in the smooth ER membrane function in the synthesis of certain kinds of molecules, such as lipids.

smooth muscle
Muscle made up of cells without striations, found in the walls of organs such as the digestive tract, urinary bladder, and arteries.

solute (*sol′-yūt*)
A substance that is dissolved in a liquid (which is called the solvent) to form a solution.

solution
A liquid consisting of a homogeneous mixture of two or more substances: a dissolving agent, the solvent, and a substance that is dissolved, the solute.

solvent
The dissolving agent in a solution. Water is the most versatile known solvent.

somatic cell (*sō-mat′-ik*)
Any cell in a multicellular organism except a sperm or egg cell or a cell that develops into a sperm or egg; a body cell.

speciation (*spē′-sē-ā′-shun*)
An evolutionary process in which one species splits into two or more species.

species
A group of populations whose members possess similar anatomical characteristics and have the ability to interbreed. *See also* biological species concept.

species diversity
The variety of species that make up a biological community; the number and relative abundance of species in a biological community.

species richness
The total number of different species in a community; one component of species diversity.

sperm
A male gamete.

spermatogenesis (*sper-mat′-ō-jen′-uh-sis*)
The formation of sperm cells.

spermicide
A sperm-killing chemical, in the form of a cream, jelly, or foam, that works with a barrier device as a method of contraception.

spinal cord
In vertebrates, a jellylike bundle of nerve fibers located within the vertebral column. The spinal cord and the brain together make up the central nervous system.

sponge
An aquatic stationary animal characterized by a highly porous body, choanocytes, and no true tissues.

spontaneous generation
The incorrect notion that life can emerge from nonliving matter.

spore
(1) In plants and algae, a haploid cell that can develop into a multicellular haploid individual, the gametophyte, without fusing with another cell. (2) In fungi, a haploid cell that germinates to produce a mycelium.

sporophyte (*spōr′-uh-fīt*)
The multicellular diploid form in the life cycle of organisms undergoing alternation of generations; results from

a union of gametes and meiotically produces haploid spores that grow into the gametophyte generation.

stabilizing selection
Natural selection that favors intermediate variants by acting against extreme phenotypes.

stamen (*stā′-men*)
A pollen-producing part of a flower, consisting of a stalk (filament) and an anther.

starch
A storage polysaccharide found in the roots of plants and certain other cells; a polymer of glucose.

start codon (*kō′-don*)
On mRNA, the specific three-nucleotide sequence (AUG) to which an initiator tRNA molecule binds, starting translation of genetic information.

stem
That part of a plant's shoot system that generally grows above the ground and supports the leaves and reproductive structures.

stem cell
A relatively unspecialized cell that can give rise to one or more types of specialized cells. *See* embryonic stem cell (ES cell); adult stem cell.

steroid (*stir′-oyd*)
A type of lipid whose carbon skeleton is in the form of four fused rings: three 6-sided rings and one 5-sided ring. Examples are cholesterol, testosterone, and estrogen.

stigma (*stig′-muh*)
(plural, **stigmata**) The sticky tip of a flower's carpel that traps pollen.

stimulus
(plural, **stimuli**) In a nervous system, a factor that triggers a nerve signal.

stoma (*stō′-muh*)
(plural, **stomata**) A pore surrounded by guard cells in the epidermis of a leaf. When stomata are open, CO_2 enters the leaf, and water and O_2 exit. A plant conserves water when its stomata are closed.

stomach
A pouch-like organ in a digestive tube that grinds and churns food and may store it temporarily.

stop codon (*kō′-don*)
In mRNA, one of three triplets (UAG, UAA, UGA) that signal gene translation to stop.

STR analysis
A method of DNA profiling that compares the lengths of STR sequences at specific sites in the genome.

stroma (*strō′-muh*)
A thick fluid enclosed by the inner membrane of a chloroplast. Sugars are made in the stroma by the enzymes of the Calvin cycle.

substrate
(1) A specific substance (reactant) on which an enzyme acts. Each enzyme recognizes only the specific substrate of the reaction it catalyzes. (2) A surface in or on which an organism lives.

sugar sink
A plant organ that is a net consumer or storer of sugar. Growing roots, shoot tips, stems, and fruits are sugar sinks supplied by phloem.

sugar source
A plant organ in which sugar is being produced by either photosynthesis or the breakdown of starch. Mature leaves are the primary sugar sources of plants.

sugar-phosphate backbone
The alternating chain of sugar and phosphate to which DNA and RNA nitrogenous bases are attached.

supporting cell
In the nervous system, a cell that protects, insulates, and reinforces a neuron.

survivorship curve
A plot of the number of individuals that are still alive at each age in the maximum life span; one way to represent age-specific mortality.

sustainability
The goal of developing, managing, and conserving Earth's resources in ways that meet the needs of people today without compromising the ability of future generations to meet their needs.

sustainable development
The long-term prosperity of human societies and the ecosystems that support them.

swim bladder
A gas-filled internal sac that helps bony fishes maintain buoyancy.

symbiosis (*sim′-bē-ō′-sis*)
An interaction between organisms of different species in which one species, the symbiont, lives in or on another species, the host.

sympathetic division
One of two sets of neurons in the autonomic nervous system; generally prepares the body for energy-consuming activities ("fight or flight"). *See also* parasympathetic division.

sympatric speciation
The formation of a new species in populations that live in the same geographic area. *See also* allopatric speciation.

synapse (*sin′-aps*)
A junction, or relay point, between two neurons or between a neuron and an effector cell. Electrical and chemical signals are relayed from one cell to another at a synapse.

synaptic cleft (*sin-ap′-tik*)
A narrow gap separating the synaptic terminal of a transmitting neuron from a receiving neuron or an effector cell.

synaptic terminal
The bulb-like structure at the tip of a transmitting neuron's axon, where signals are sent to another neuron or to an effector cell.

systematics
A discipline of biology that focuses on classifying organisms and determining their evolutionary relationships.

systemic circuit
One of two main blood circuits in terrestrial vertebrates; conveys blood between the heart and the rest of the body. *See also* pulmonary circuit.

systole (*sis′-tō-lē*)
The contraction stage of the cardiac cycle, when the heart chambers actively pump blood. *See also* diastole.

T

T cell
A type of lymphocyte that matures in the thymus and is responsible for the cell-mediated immune response. *See also* B cell.

taiga (*tī′-guh*)
The northern coniferous forest, characterized by long, snowy winters and short, wet summers. Taiga extends across North America and Eurasia, to the southern border of the arctic tundra; it is also found just below alpine tundra on mountainsides in temperate zones.

tail
Extra nucleotides added at the end of an RNA transcript in the nucleus of a eukaryotic cell.

target cell
A cell that responds to a regulatory signal, such as a hormone.

taxonomy
The branch of biology concerned with identifying, naming, and classifying species.

telophase
The fourth and final stage of mitosis, during which daughter nuclei form at the two poles of a cell. Telophase usually occurs together with cytokinesis.

temperate broadleaf forest
A terrestrial biome located throughout midlatitude regions where there is sufficient moisture to support the growth of large, broadleaf deciduous trees.

temperate grassland
A terrestrial biome located in the temperate zone and characterized by low rainfall and nonwoody vegetation. Tree growth is hindered by occasional fires and periodic severe drought.

temperate rain forest
A coniferous forest of coastal North America (from Alaska to Oregon) supported by warm, moist air from the Pacific Ocean.

temperate zones
Latitudes between the tropics and the Arctic Circle in the north and the Antarctic Circle in the south; regions with milder climates than the tropics or polar regions.

temperature
A measure of the intensity of heat, reflecting the average kinetic energy or speed of molecules.

tendon
Fibrous connective tissue connecting a muscle to a bone.

terminal bud
Embryonic tissue at the tip of a shoot, made up of developing leaves and a compact series of nodes and internodes.

terminator
A special sequence of nucleotides in DNA that marks the end of a gene. It signals RNA polymerase to release the newly made RNA molecule, which then departs from the gene.

tertiary consumer (*ter′-shē-ār-ē*)
An organism that eats secondary consumers.

testcross
The mating between an individual of unknown genotype for a particular character and an individual that is homozygous recessive for that same character.

testicle
A structural component of the male reproductive system consisting of a testis and scrotum.

testis
(plural, **testes**) The male gonad in an animal. The testis produces sperm and, in many species, reproductive hormones.

tetrapod
A vertebrate with four limbs. Tetrapods include mammals, amphibians, and reptiles (including birds).

theory
A widely accepted explanatory idea that is broad in scope and supported by a large body of evidence.

therapeutic cloning
The cloning of human cells by nuclear transplantation for therapeutic purposes, such as the replacement of body cells that have been irreversibly damaged by disease or injury. *See also* nuclear transplantation; reproductive cloning.

thermoreceptor
A sensory receptor that detects heat or cold.

thermoregulation
The maintenance of internal temperature within a range that allows cells to function efficiently.

thick filament
The thicker of the two types of filaments that make up a sarcomere, consisting of the protein myosin.

thigmotropism (*thig′-mō-trō′-pizm*)
Growth of a plant in response to touch.

thin filament
The thinner of the two types of filaments that make up a sarcomere, consisting of the protein actin.

threatened species
As defined in the U.S. Endangered Species Act, a species that is likely to become endangered in the foreseeable future throughout all or a significant portion of its range.

three-domain system
A system of taxonomic classification based on three basic groups: Bacteria, Archaea, and Eukarya.

threshold
The minimum change in a membrane's voltage that must occur to generate a nerve signal (action potential).

thylakoid (*thī′-luh-koyd*)
One of a number of disk-shaped membranous sacs inside a chloroplast. Thylakoid membranes contain chlorophyll and the enzymes of the light reactions of photosynthesis. A stack of thylakoids is called a granum.

thymine (T) (*thī′-mēn*)
A single-ring nitrogenous base found in DNA.

thyroid gland (*thī′-royd*)
An endocrine gland, located in the neck, that secretes hormones that increase oxygen consumption and metabolic rate and help regulate development and maturation.

tissue
An integrated group of similar cells that performs a specific function within a multicellular organism.

tissue system
An organized collection of plant tissues. The organs of plants (such as roots, stems, and leaves) are formed from the dermal, vascular, and ground tissue systems.

tongue
A muscular organ of the mouth that helps to taste and swallow food.

trace element
An element that is essential for the survival of an organism but is needed in only minute quantities.

trachea (*trā′-kē-uh*)
(plural, **tracheae**) (1) The windpipe; the portion of the respiratory tube between the larynx and the bronchi. (2) One of many tiny tubes that branch throughout an insect's body, enabling gas exchange between outside air and body cells.

tracheal system
In insects, an extensive network of branching internal tubes called tracheae, used in respiration.

tracheid (*trā′-kē-id*)
A tapered, porous, water-conducting, supportive cell in plants. Chains of tracheids or vessel elements make up the water-conducting, supportive tubes in xylem.

trait
A variant of a character found within a population, such as purple flowers in pea plants.

trans fats
An unsaturated fatty acid produced by the partial hydrogenation of vegetable oils and present in hardened vegetable oils, most margarines, many commercial baked foods, and many fried foods.

transcription
The synthesis of RNA on a DNA template.

transcription factor
In the eukaryotic cell, a protein that functions in initiating or regulating transcription. Transcription factors bind to DNA or to other proteins that bind to DNA.

transfer RNA (tRNA)
A type of ribonucleic acid that functions as an interpreter in translation. Each tRNA molecule has a specific anticodon, picks up a specific amino acid, and conveys the amino acid to the appropriate codon on mRNA.

transgenic organism
An organism that contains genes from another organism, typically of another species.

translation
The synthesis of a polypeptide using the genetic information encoded in an mRNA molecule. There is a change of "language" from nucleotides to amino acids.

transmission electron microscope (TEM)
A microscope that uses an electron beam to study the internal structure of thinly sectioned specimens.

transpiration
The evaporative loss of water from a plant.

transpiration-cohesion-tension mechanism
The transport mechanism of xylem sap whereby transpiration exerts a pull that is relayed downward along a string of water molecules held together by cohesion and helped upward by adhesion.

transport protein
A membrane protein that helps move substances across a cell membrane.

transport vesicle
A tiny membranous sphere in a cell's cytoplasm carrying molecules produced by the cell. The vesicle buds from the endoplasmic reticulum or Golgi apparatus and eventually fuses with another organelle or the plasma membrane, releasing its contents.

triglyceride (*trī-glis′-uh-rīd*)
A dietary fat that consists of a molecule of glycerol linked to three molecules of fatty acids.

trimester
In human development, one of three 3-month-long periods of pregnancy.

trisomy 21
See Down syndrome.

trophic structure (*trō′-fik*)
The feeding relationships among the various species in a community.

trophoblast (*trōf′-ō-blast*)
In mammalian development, the outer portion of a blastocyst. Cells of the trophoblast secrete enzymes that enable the blastocyst to implant in the endometrium of the mother's uterus.

tropical forest
A terrestrial biome characterized by warm temperatures year-round.

tropics
Region between the Tropic of Cancer and the Tropic of Capricorn; latitudes between 23.5° north and south.

tropism (*trō′-pizm*)
A growth response that makes a plant grow toward or away from a stimulus.

tubal ligation
A means of sterilization in which a woman's two oviducts (fallopian tubes) are tied closed to prevent eggs from reaching the uterus. A segment of each oviduct is removed.

tuber
An enlargement at the end of a rhizome, in which food is stored.
tubule
A thin tube within the internal structure of the human kidney.
tumor
An abnormal mass of cells that forms within otherwise normal tissue.
tumor-suppressor gene
A gene whose product inhibits cell division, thereby preventing uncontrolled cell growth.
tundra
A terrestrial biome characterized by bitterly cold temperatures. Plant life is limited to dwarf woody shrubs, grasses, mosses, and lichens. Arctic tundra has permanently frozen subsoil (permafrost); alpine tundra, found at high elevations, lacks permafrost.
tunicate
One of a group of stationary invertebrate chordates.

U

umbilical cord
A structure containing arteries and veins that connects a developing embryo to the placenta of the mother.
unsaturated
Pertaining to fats and fatty acids of which hydrocarbon chains lack the maximum number of hydrogen atoms and therefore have one or more double covalent bonds. Because of their bent shape, unsaturated fats and fatty acids tend to stay liquid at room temperature.
uracil (U) (*yū′-ruh-sil*)
A single-ring nitrogenous base found in RNA.
ureter (*yū-rē′-ter* or *yū′-reh-ter*)
A duct that conveys urine from the kidney to the urinary bladder.
urethra (*yū-rē′-thruh*)
A duct that conveys urine from the urinary bladder to outside the body. In the male, the urethra also conveys semen out of the body during ejaculation.
urinary bladder
The pouch where urine is stored before elimination.
urine
Concentrated filtrate produced by the kidneys and excreted via the bladder.
uterus (*yū′-ter-us*)
In the reproductive system of a mammalian female, the organ where the development of young occurs; the womb.

V

vaccination (*vak′-suh-nā′-shun*)
A procedure that presents the immune system with a harmless version of a pathogen, thereby stimulating an adaptive defense when the pathogen itself is encountered.
vaccine (*vak-sēn′*)
A harmless version or piece of a pathogen (a disease-causing virus or organism) used to stimulate a host organism's immune system to mount a long-term defense against the pathogen.
vacuole (*vak′-ū-ōl*)
A membrane-enclosed sac, part of the endomembrane system of a eukaryotic cell, having diverse functions.
vagina (*vuh-jī′-nuh*)
Part of the female reproductive system between the uterus and the outside opening; the birth canal in mammals. The vagina accommodates the male's penis and receives sperm during copulation.
vas deferens (*vas def′-er-enz*)
(plural, **vasa deferentia**) Part of the male reproductive system that conveys sperm away from the testis; the sperm duct; in humans, the tube that conveys sperm between the epididymis and the common duct that leads to the urethra.
vascular cambium
(*vas′-kyū-ler kam′-bē-um*)
In plants, a cylinder of meristem tissue found between the primary xylem and phloem. During secondary growth, the vascular cambium produces secondary xylem and phloem.
vascular tissue
Plant tissue consisting of cells joined into tubes that transport water and nutrients throughout the plant body. Xylem and phloem make up vascular tissue.
vascular tissue system
A system formed by xylem and phloem throughout a plant, serving as a long-distance transport system for water and nutrients, respectively.
vasectomy (*vuh-sek′-tuh-mē*)
Surgical removal of a section of the two sperm ducts (vasa deferentia) to prevent sperm from reaching the urethra; a means of sterilization in the male.
vector
A piece of DNA, usually a plasmid or a viral genome, that is used to move genes from one cell to another.
vein
(1) In animals, a vessel that returns blood to the heart. (2) In plants, a vascular bundle in a leaf, composed of xylem and phloem.
ventricle (*ven′-truh-kul*)
A heart chamber that pumps blood out of the heart to the body or lungs via arteries.
venule (*ven′-yūl*)
A small vessel that conveys blood between a capillary bed and a vein.
vertebrate (*ver′-tuh-brāt*)
A chordate animal with a backbone. Vertebrates include lampreys, cartilaginous fishes, bony fishes, amphibians, reptiles (including birds), and mammals.
vessel element
A short, open-ended, water-conducting, supportive cell in plants. Chains of vessel elements or tracheids make up the water-conducting, supportive tubes in xylem.
vestigial structure
A structure of marginal, if any, importance to an organism. Vestigial structures are historical remnants of structures that had important functions in ancestors.
virus
A microscopic particle capable of infecting cells of living organisms and inserting its genetic material. Viruses have a very simple structure and are generally not considered to be alive because they do not display all of the characteristics associated with life.
vitamin
An organic nutrient that an organism requires in very small quantities. Vitamins generally function as coenzymes.
vitreous humor (*vit′-rē-us hyū′-mer*)
A jellylike substance that fills the space behind the lens in the vertebrate eye and helps maintain the shape of the eye.
vocal cord
One of a pair of tissues in the larynx. Air rushing past the tensed vocal cords makes them vibrate, producing sounds.
vulva
The outer features of the female reproductive anatomy.

W

warning coloration
The bright color pattern, often yellow, red, or orange in combination with black, of animals that have effective chemical defenses.
water vascular system
In echinoderms, a radially arranged system of water-filled canals that branch into extensions called tube feet. The system provides movement and circulates water, facilitating gas exchange and waste disposal.
wavelength
The distance between crests of adjacent waves, such as those of the electromagnetic spectrum.
wetland
An ecosystem intermediate between an aquatic ecosystem and a terrestrial ecosystem. Wetland soil is saturated with water permanently or periodically.
white blood cell
A blood cell that functions in defending the body against infections; also called a leukocyte.
whole-genome shotgun method
A method for determining the DNA sequence of an entire genome by cutting it into small fragments, sequencing each fragment, and then placing the fragments in the proper order.
wild-type trait
The trait most commonly found in nature.
wood
Secondary xylem of a plant.

X

X chromosome inactivation
In female mammals, the inactivation of one X chromosome in each somatic cell. Once X inactivation occurs in a given cell (during embryonic development), all descendants of that cell will have the same copy of the X chromosome inactivated.

xylem (*zī′-lum*)
The portion of a plant's vascular system that provides support and conveys water and inorganic nutrients from the roots to the rest of the plant. Xylem consists mainly of vessel elements and/or tracheids, water-conducting cells.

xylem sap
The solution of inorganic nutrients conveyed in xylem tissue from a plant's roots to its shoots.

Z

zooplankton
In aquatic environments, free-floating animals, including many microscopic ones.

zygote (*zī′-gōt*)
The fertilized egg, which is diploid, that results from the union of haploid gametes (sperm and egg) during fertilization.

Index

Page numbers with *f* indicate figure, *t* indicate table, and those in bold indicate page where defined as key term.

A

Abdomen, arthropod, 347*f*, 350*f*
Abiotic factors, **375**
  in biogeochemical cycles, 440
  of biosphere, 376–77
  in ecology, 375
  in ecosystem ecology, 437 (*see also* Chemical cycling; Energy flow)
  limiting population growth, 411
  in terrestrial biomes, 386
Abiotic reservoirs, **440**. *See also* Chemical cycling
Abiotic synthesis of life, 296–98
ABO blood groups, **159**, 503
Abortion, RU-486 and, 560
Abscisic acid, **635**
Absolute age, fossil, 282
Absorption, **329**, **476**, 482–84*f*
Abstinence, sexual, 559–61
Acclimation, **378**
Acetic acid, 98
Acetylcholine, 580
Acetyl CoA, 98
Achondroplasia (dwarfism), **156**, 236, 541
Acidification, ocean, 33
Acid precipitation, 391, 428
Acid reflux, 481
Acids, **32**
  bases, pH, and, 32–33
  in human gastric juice, 480–81
Acquired defenses. *See* Adaptive defenses
Acromegaly, 541
Acrosome, 562
ACTH (adrenocorticotropic hormone), 545
Actin, 596
Actinomycetes, 300*f*
Action potentials, **577**
  in nervous system signal transmission, 577–80
  in vision, 590
Activation energy, enzymes and, **80**
Activators, DNA, **203**
Active site, enzyme, **82**
Active transport, **86**
Adam's apples, 480
Adaptations, evolutionary. *See* Evolutionary adaptations
Adaptive coloration, predation and, 430
Adaptive defenses, **518**, 521–27
  B cells and humoral immune response of, 526
  case study on HIV as cause of AIDS and, 523
  clonal selection and multiplication of lymphocytes by, 524
  innate defenses vs., 518
  memory cells and secondary immune response of, 525
  recognition of invading antigens by, 522
  T cell and B cell lymphocytes of, 521
  T cells and cell-mediated immune response of, 526–27
  vaccination and, 525
Addiction
  hypothalamus pleasure center and, 583
  smooth ER and, 65
Adélie penguins, effect of global climate change on, 373, 399
Adenine (A), 7, 49–50, 174–**75**
Adenoviruses, 188*f*
ADH (antidiuretic hormone), 470, 540
ADHD (attention deficit hyperactivity disorder), 580
Adhesion, **629**–30
Adipose tissue, 16, 43, **459**
ADP (adenosine diphosphate), **79**–80
Adrenal cortex, 539*t*, **544**–45
Adrenal glands, **544**
  in cell signaling, 87
  endocrine system functions of, 539*t*, 544–45
Adrenaline. *See* Epinephrine (adrenaline)
Adrenal medulla, 539*t*, **544**–45
Adrenocorticotropic hormone (ACTH), 545
Adult stem cells, therapeutic cloning using, **210**. *See also* Stem cells
Aerobic capacity, high-altitude athletic training for, 504
Aerobic endosymbionts, 306
Aerobic exercise case study, 31–32
Aerobic processes, **94**. *See also* Aerobic vs. anaerobic lifestyles; Cellular respiration
Aerobic vs. anaerobic lifestyles
  evolution of glycolysis and, 103
  muscle fatigue as lactic acid accumulation from fermentation, 102
  slow-twitch vs. fast-twitch muscle fibers and, 91
Africa, origin of *Homo sapiens* in, 366
African mega mantises, 637
Afterbirth, 568
Agar gel, 310
Age structure, population, **405**, 418–19
Aggressive behavior, androgens and male, 547
Agriculture
  angiosperms in, 326
  auxins in, 633–34
  biological control of pests in, 414–15
  case study on drought and failure of, in Lost Colony of Roanoke, 616
  cheatgrass as invasive species and, 413–14
  deforestation for, 389, 392
  effects of bee colony collapse disorder on, 621
  fungal pests and, 330
  history of cultivation of coffee plants in, 604–5
  insects as pests in, 352
  integrated pest management in, 416
  loss of plant diversity through slash-and-burn, 327
  nutrient pollution by, 443
  organic farming and sustainable, 627, 634
  phosphorus and nitrogen in, 441–42
  plant cloning in, 207
  roundworms as pests in, 346
  in temperate grassland biomes, 388
AIDS (acquired immunodeficiency syndrome), **192**
  HIV and, 190, 192–94, 523 (*see also* HIV (human immunodeficiency virus))
  search for vaccine for, 516–17
  as sexually transmitted disease, 561
Ain, Dr. Michael C., 156*f*
Air pollution
  declining biodiversity and, 428
  effects of, on human lungs, 510
  tobacco smoke as, 512–13
Air pressure, breathing and, 511
Alcohol
  effects of, on fetal development, 565
  effects of, on human brain, 580
Alcoholic fermentation, 103, 107
Algae, **307**, 310
  in coral reef mutualism, 430
  in freshwater biomes, 380
  in lichens, 332
  in marine biomes, 382
  nutrient pollution and, 443
  photosynthetic, 108
  as photosynthetic protists, 307
  reproduction of, 317
  structural adaptations of, 316*f*
  unicellular and colonial, 310
Ali, Muhammad, 231*f*
Alimentary canal, **478**–79, 482
Alkaptonuria, 178
Allantois, 565
Alleles, **148**. *See also* Genes
  ABO blood groups as example of codominant, 159
  dominant vs. recessive, 148
  gene pools of, 256–59
  human genetic disorders and, 154–56
  law of segregation and, 148–49
  sickle-cell disease as example of pleiotropy by, 160
Allergens, **528**
Allergies, **528**
Alligators, 358
Allopatric speciation, **274**–75
Alprazolam, 580
Alternation of generations, **320**, 322–23
Alternative RNA splicing, **204**
Altitude
  athletic training at high, 504
  human adaptations to high, 513
  vegetation types and, 384
Alvarez, Luis and Walter, 284–85
Alveoli, **510**, 512
Alvin research submarine, 299*f*
Alzheimer's disease, 48, 231, **586**
Amazonian forest fragmentation case study, 446
American bison, 428
American elm trees, 330
American pika, 377
Amine hormones, 537
Amine neurotransmitters, 580
Amino acids, **46**
  case study on abiotic formation of, 297
  genes and sequences of, 48
  human essential, 486
  as monomers of proteins, 46 (*see also* Proteins)
  neurotransmitters derived from, 580
  synthesis of, in gene expression, 182–83 (*see also* Gene expression)
  systematics and sequences of, 287
  triplet genetic code for, 179–80
Amino groups, 46
Ammonifying bacteria, 628
Ammonium, nitrogen fixation and, 442, 628–29
Amniocentesis, 157
Amnion, 565
Amniotes, **358**
  reptiles and mammals as, 358
  vertebrates as, 355*f*
Amniotic eggs, 355*f*, **358**
Amniotic fluid, 565
Amoebas, 69, **308**, 464
Amoebic dysentery, 308

Amoebocytes, 341
Amoeboid movements, cytoskeletons and, 69
Amphetamines, 580
Amphibians, **357**
  characteristics of, 357
  emergence of, in history of life, 295
  extinctions of species of, 426
  positive pressure breathing of, 511
Ampicillin, 55
Anabolic steroids, athletic abuse of, 45, 534–35, 546. *See also* Steroid hormones
Anaerobic processes, **101**. *See also* Aerobic vs. anaerobic lifestyles; Fermentation
Analogies, 286–**87**
Anaphase, mitosis, **127**, 134*f*
Anaphase I, meiosis I, 132*f*, 134*f*
Anaphase II, meiosis II, 133*f*
Anaphylactic shock, 528
Anatomical responses to environmental conditions, 379
Anatomical thermoregulation adaptations, 471
Anatomy, 250, **457**. *See also* Animal structure and function
Ancestors, cladistics and common, 287–88
Androgens, **546**–47
Anemia, 221, **503**, 505, 512
Angina, 506
Angioplasty, 506
Angiosperms, **319**, 604–23. *See also* Plants
  agriculture and, 326, 604–5, 616, 621
  cells of, 611–12
  coffee plants as, 604–5
  drought and agricultural failure of, in Lost Colony of Roanoke, 616
  effects of bee colony collapse disorder on pollination of, 621
  fruit formation of, 620
  genetic overview of life cycle of, 618
  indeterminate growth of, 613–16 (*see also* Plant growth)
  monocots and dicots, 606
  in plant evolution, 319
  pollination and fertilization of, 618–19
  roots, stems, and leaves as plant organs of, 607–9
  seed formation of, 619
  seed germination of, 620
  sexual life cycle of, 324–26, 617–21
  structure and function of, 606–12
  structure of flowers of, 617
  terrestrial adaptations of, 322–23
  tissues and tissue systems of, 610–11
Animalia kingdom, 9, 289
Animals, 336–37, **338**–70
  adaptations of, to environmental variability, 378–79
  angiosperm pollination and dispersal by, 326*f*, 352, 619, 621, 637
  artificial selection of, 12–13*f*
  asexual and sexual reproduction of, 552–53 (*see also* Human reproduction)
  asexual reproduction by, 120–21, 137
  breeding of, by humans, 144–45
  Cambrian explosion and diversification of, 339
  cell cyle of (*see* Cell cycle, eukaryotic)
  cells of, 59, 61 (*see also* Eukaryotic cells)
  cellular respiration by mitochondria of, 68
  characteristics of, 338
  in chemical cycling, 92–93, 437, 440–43
  as chemoheterotrophs, 302
  chordates, 354–55
  communities of (*see* Communities)
  determinate growth of, 613
  digestive systems of (*see* Digestive systems)
  emergence of new senses in, 598 (*see also* Senses)
  endangered and threatened (*see* Endangered species; Threatened species)
  Eukarya domain and Animalia kingdom of, 9, 289
  evolution of, 337
  explosive diversifications of, after mass extinctions, 284
  extrahuman senses of, 574–75, 588, 592, 598–99 (*see also* Senses)
  genetically modified (GM) pharmaceutical (pharm), 222
  homeotic genes of, 205–6
  hormones and endocrine systems of, 463*f*, 536–37 (*see also* Endocrine systems; Hormones, animal)
  human lactose tolerance and dairy, 51
  humans and primates, 361–67 (*see also* Humans; Primates)
  immune systems of (*see* Immune systems)
  innate and adaptive defenses of, 518 (*see also* Adaptive defenses; Innate defenses)
  interspecific interactions of, 428–32
  invertebrates, 341–53 (*see also* Invertebrates)
  in marine biomes, 382–83
  nervous systems of, 576–80 (*see also* Nervous systems)
  number of chromosomes in cells of, 123*f*
  nutrition for, 476–78
  open and closed circulatory systems of, 496–97 (*see also* Cardiovascular systems)
  as open systems, 464
  origins of diversity of, 338–41*f*
  osmoregulation of water balance in cells of, 85
  overuse of antibiotics in raising, 71
  parasites and pathogens of, 330, 432
  phylogeny of, 340–41*f*
  polysaccharides in, 42
  populations of (*see* Populations)
  prions, infections of, 194
  regeneration of body parts by, 207
  reproductive cloning of, 208–9
  respiratory systems of, 507–8 (*see also* Respiratory systems)
  saturated fatty acids in fats of, 44
  sex chromosomes and sex-linked genes of, 165–66
  sexual reproduction by, 121, 140 (*see also* Sexual reproduction)
  structure and function of (*see* Animal structure and function)
  in terrestrial biomes, 385–86
  vertebrates, 354–60 (*see also* Vertebrates)
  viral infections of, 190–91
Animal structure and function, 454–73
  case study on python thermoregulation mechanism in, 468
  evolutionary adaptations for thermoregulation in, 471
  exchanges with external environments in, 464–65
  form fits function in, 456–57
  human thermoregulation in, 454–55
  organs and organ systems in, 461–63
  regulation of internal environments in, 465–71
  structural hierarchy of organization in, 456–63
  tissues in, 457–61
Annelids (Annelida), **345**
Annuals (plants), **613**
Annual tree growth rings, 615–16
Anorexia nervosa, **489**
Antagonistic hormones, **542**
Antagonistic muscle pairs, 596
Antarctica
  effect of global climate change on, 373
  polar ice biome of, 390
Anterior pituitary, 539*t*, **540**
Anthers, flower, **324**, **617**, 619
Anthrax bacteria, 231, 301*f*, 304
Anthrax killer investigation, genomics in, 231
Anthropoids, **361**–62
Antibiotic-resistant bacteria, 18, 55, 61, 71, 253, 304
Antibiotics
  from actinomycetes, 300*f*
  for bacterial disease, 304
  bacterial resistance to (*see* Antibiotic-resistant bacteria)
  for chlamydia, 560
  fungi and, 332
  for gastric ulcers, 481
  for meningitis, 582
  prokaryotic ribosomes as targets of, 58
Antibodies, **522**
  in allergies, 528
  B cells and, 522
  generation of effector cells by, 524
  in humoral immune response, 526
  in linking HIV to AIDS, 523
Anticancer drugs, 332
Anticoagulant drugs, 505
Anticodons, **183**–84
Antidepressant drugs, 586
Antidiuretic hormone (ADH), 470, 540
Antigen receptors, 522
Antigens, **521**–22. *See also* Lymphocytes
Antihistamines, 528
Anti-inflammatory drugs, 520, 595
Antilocapra americana, 421
Antimicrobial secretions, innate defense of, 518
Anus, 478, **484**
Anvil, ear, 592–93
Aorta, 498, 506
Apes, 361–62
Aphids, population growth of, 411
Aphotic zone, **380**, 382
Apical dominance, **608**
Apical meristems, **613**–14, 633
Apicomplexans, **308**–9*f*
Appendicitis, 484
Appendicular skeleton, **594**
Appendix, **484**
Aquatic biomes. *See also* Freshwater biomes; Marine biomes
  abiotic factors in, 376–77
  animal circulatory systems and, 507–8

animal osmoregulation in, 468–69
animal respiration in, 507–8*f*
characteristics of, 380
history of life and, 295
nutrient pollution of, 443
water in, as abiotic reservoir for biogeochemical cycles, 440
Aqueous humor, **589**
Aqueous solutions, **31**
Arabidopsis thaliana genome, 230
Arachnids, **348**
Archaea, **302**. *See also* Prokaryotes
Archaea domain of, 9, 288, 302
cells of (*see* Prokaryotic cells)
characteristics of, 302–3
emergence of, in history of life, 294
Arctic
effect of global climate change on, 373
tundra biome of, 390
Ardipithecus, 364
Argynnis paphia, 396
Aristotle, 245
Artemesinin, 243
Arteries, **497**
animal, 497
blood flow through human, 498, 501
tissues of, 500–501
Arterioles, **497**, 501*f*
Arthritis, **595**
Arthropods (Arthropoda), **347**–52
arachnids, 348
Burgess Shale fossils of, 339
crustaceans, 349
general characteristics of, 347
insects, 350–52 (*see also* Insects)
millipedes and centipedes, 350
Artificial enzymes, 81
Artificial hearts, 506
Artificial movement corridors, 445
Artificial organisms, synthesis of, 293
Artificial pacemakers, 500
Artificial selection
of bread wheat and food crops, 276
dog breeding as, 144–45, 151, 156, 167
in engineering of enzymes, 81
selective breeding as, 12–13*f*
Artificial vesicles, 87
Asexual reproduction, **122**, **552**, **617**. *See also* Reproduction
angiosperm, 617
animal, 552
artificial (*see* Cloning)
of bdelloid rotifers, 137
cell division for, 122–23*f*
evolutionary advantages of, 140
fungal, 329
by Komodo dragons, 120–21
plant runners as, 608
sexual reproduction vs., 122, 130 (*see also* Sexual reproduction)
A site, ribosome, 183–84
Aspirin, 520, 588
Association areas, cerebral cortex, **584**
Astigmatism, **591**
Atchafalaya National Wildlife Refuge, 424
Atherosclerosis, **44**, **506**
Athletes
abuse of anabolic steroids by, 45, 534–35, 546
abuse of EPO by, 503–4, 537
abuse of HCG by, 559
abuse of HGH by, 541
blood doping by, 101, 221, 503–4
carbohydrate loading by, 42
cardiovascular and respiratory systems and endurance, 494–95
cortisone treatment of injuries of, 545
evolution of high-altitude adaptations and, 513
heat illnesses of, 455
high-altitude training for, 504
integration of stimulus and locomotor response in, 599
MRSA (methicillin-resistant *Staphylococcus aureus*) and, 18
Athlete's foot, 330
Atlantic cod fishery collapse, 413
Atmosphere
as abiotic reservoir for carbon, 440, 441
as abiotic reservoir for nitrogen, 442
greenhouse gases in, 394–95
oxygen in, 507
Atomic model, DNA, 176*f*
Atomic number, 24*f*, **25**
Atoms, **25**
electron arrangement and properties of, 26
isotopes and, 25–26
as level of life, 5*f*
structure of, 25
ATP (adenosine triphosphate), **79**
active transport and, 86
in aerobic vs. anaerobic lifestyles, 91
ATP cycle of, 80
in Calvin cycle, 115
in cellular respiration, 94–100 (*see also* Cellular respiration)
in cellular work, 79–80
in chemical cycling between photosynthesis and cellular respiration, 92–93
in fermentation, 101–3
generation of, by light reactions, 113–14
in muscle contraction, 597
nanotechnology and production of, 75
in photosynthesis, 109–10
production of, by mitochondria, 68
structure of, 79
yield of, during cellular respiration, 100
ATP cycle, 80
ATP synthases, **99**, 114
Atrioventricular (AV) node, **500**
Atrium, heart, **496**, 498–99
Attachment functions, membrane proteins and, 83*f*
Attention deficit hyperactivity disorder (ADHD), 580
Auditory canal, **592**–93
Auditory nerve, 592–93
Auditory reception. *See* Hearing
Australia, marsupials of, 249, 283, 360
Australopithecus, 364
Autoclaves, 301
Autoimmune diseases, **529**, 595
Automated DNA-synthesizing machines, 225
Automated external defibrillators, 500
Autonomic nervous system, **582**. *See also* Nervous systems
Autosomal disorders, 154–56
types of, 155*t*
Autosomes, **131**, 154–56, 165
Autotrophs, **92**, 108, 302, 307, 432–33
Auxins, **632**–36
Avian flu virus, 172–73, 194
AV (atrioventricular) node, **500**
Axial skeleton, **594**
Axillary buds, **608**, 634
Axolotl, paedomorphosis of, 279
Axons, nerve, **576**–78
AZT anti-AIDS drug, 187, 193

B

Baboons, 361
Baby boom, U.S., 418–19
Bacilli, **300**
Bacillus anthracis. *See* Anthrax bacteria
Bacitracin, 55
Backbones, 354. *See also* Spinal columns
Bacteria, **302**. *See also* Prokaryotes
ammonifying, 628
anthrax, 231, 301*f*, 304
antibiotic-resistant (*see* Antibiotic-resistant bacteria)
applications of genetically modified, 220–21
Bacteria domain of, 9, 288, 302
bioremediation using, 447
bioterrorism and, 231, 304, 525 (*see also* Bioterrorism)
cells of (*see* Prokaryotic cells)
complement proteins as innate defense against, 519
conjunctivitis and, 589
destruction of, by lysosome enzymes, 66
emergence of, in history of life, 294
gastric ulcers and, 481
gene regulation in, 200–201
genetic engineering of, for insulin production, 8
infection of small intestine by, 483
infectious, 54–55, 58, 467
of large intestine, 484
in lichens, 332
meningitis and, 582
mutations and genetic variation in, 258
pathogenic, 303–4, 432
as photosynthetic autotrophs, 108*f*
in plant nitrogen nutrition, 442, 628–29, 637
plasmids of, in gene cloning, 222–24
root nodule, 629
sequencing of whole genomes of, 230
sexually transmitted diseases and, 560–61*t*
significance of, to human life, 299
symbiotic, 332
viruses that attack, 188–89
Bacteria domain, 9, 288, **302**. *See also* Bacteria
Bacteriophages, **188**–89
Baker's yeast, genome of, 230
Bald cypress trees, tree ring data from, 616
Ball-and-socket joints, **594**
Ball-and-stick models, 27*f*
Bantengs, 208–9*f*
Bark, **616**
Bark beetles, global climate change and, 397
Barnacles, 349*f*
Barrier methods, contraceptive, 560
Barriers, reproductive. *See* Reproductive barriers
Basal metabolic rate (BMR), **485**
Baseball, steroid abuse and, 534–35
Base pairing, DNA, 175–77

Bases, acids and, **32**–33
Bases, nitrogenous, DNA and RNA, 7–8, 49–50, 174–76, 179
Base substitution mutations, 186–87
Basilar membrane, ear, 592–93
Basking, thermoregulation by, 358, 471
Bathing, thermoregulation by, 471
Bats, 360
B cells, **521**
  in allergies, 528
  clonal selection and primary immune response of, 524–25
  humoral immune response of, 526–27
  as lymphocytes, 521
  recognition of invading antigens by, 522
Bdelloid rotifers, asexual reproduction of, 137
Beadle, George, 178
Beagle voyage, Charles Darwin's, 246–47
Bears, evolution of, 10, 12
Beef, food energy for humans from, 439
Bees, colony collapse disorder of, 621
Behavioral isolation, 272–73
Behavioral responses to environmental conditions, 379
Behavioral thermoregulation adaptations, 471
Benign tumors, **129**, 212. *See also* Cancer
Benthic realm, **380**, 382
Benthos, 380–81
Beta-carotene, 590
Biennials (plants), **613**
Bilateral symmetry, **340**
Bile, **482**
Binary fission, **301**
Binomial names, taxonomy and, **285**
Biodiesel, 107
Biodiversity, 8–9, 268–91, **426**
  causes of loss of, 427–28
  conservation biology as study of loss of, 444–49
  Charles Darwin's observations of, 244
  DNA and unity in, 9
  ecosystem diversity, 427
  ecosystem services of, 424–25
  effects of mass extinction of dinosaurs on, 284–85, 289
  effects of tropical forest fragmentation on, 446
  in freshwater biomes, 380
  genetic diversity, 426
  grouping of species in taxonomy of, 8–9
  hot spots of, 444
  human biophilia and, 448–49
  macroevolution of biological novelty and, 278–85 (*see also* Macroevolution)
  mass extinctions and, 268–69, 284–85, 289
  mutations as source of, 187
  origins of species in speciation and, 270–77 (*see also* Speciation)
  sixth mass extinction and, 268–69
  species diversity, 426
  systematics in classifying, 285–89 (*see also* Systematics; Taxonomy)
  unity in, 9, 180, 547
Biodiversity hot spots, **444**
Bioethanol, 93, 106–7
Biofilms, **301**
Biofuels
  algae and, 310
  deforestation for, 392
  photosynthesis and, 93, 106–7
Biogenesis, **296**
Biogeochemical cycles, **440**
  in chemical cycling, 440–43 (*see also* Chemical cycling)
  prokaryotes and, 299
Biogeography, **249**
Bioinformatics, 232
Biological clock, 583
Biological communities. *See* Communities
Biological control of pests, **414**–16
Biological diversity. *See* Biodiversity
Biological Dynamics of Forest Fragmentation Project (BDFFP), 446
Biological invasions, 402–3, 415, 421. *See also* Invasive species
Biological magnification, **433**
Biological molecules, 36–53
  abiotic synthesis of, in origin of life, 296–98
  breakdown of, by lysosome enzymes, 66
  carbohydrates as, 40–42
  exocytosis, endocytosis, and transport of large, across membranes, 86
  heterotrophs and, 302
  lactose intolerance and, 36–37, 51–52
  lipids as, 43–45
  nucleic acids as, 49–50
  as organic compounds, 38–39
  proteins as, 46–48
Biological novelty, evolution of. *See* Macroevolution
Biological species concept, **271**
Biological weapons, bacterial, 231, 304, 525. *See also* Bioterrorism
Biology, **4**
  anatomy and physiology, 457
  bioinformatics in, 232
  cells in (*see* Cells)
  conservation biology, 444–49 (*see also* Conservation biology)
  ecology (*see* Ecology)
  essential chemistry for (*see* Chemistry)
  everyday life and, 2–3, 15–16, 18
  evo-devo (evolutionary developmental), 279
  evolution as unifying theme of, 10–13 (*see also* Evolution)
  genetics in (*see* Genetics)
  molecular biology as study of heredity, 174
  molecules of life in (*see* Biological molecules)
  photosynthesis in (*see* Photosynthesis)
  science and, 4, 14–18 (*see also* Case studies; Science)
  scope of life and, 4–9 (*see also* Life)
  society and (*see* Social issues)
  synthetic, 293
  taxonomy as branch of, 9
Biomass, **438**
  biofuels and, 107
  in ecosystem energy flow, 438
  of prokaryotes, 299
Biomes, **380**–93. *See also* Biosphere
  climate and distribution of terrestrial, 384–85
  freshwater, 380–81
  global water cycle and, 391
  human impacts on, 392–93
  marine, 382–83
  terrestrial, 384–90
Biophilia, **448**–49
Bioprospecting, genetic diversity and, 426
Bioremediation, **305**, **447**
  phytoremediation, 624–25
  in restoration ecology, 447
  using prokaryotes, 305
Biosafety Protocol, 236
Biosphere, **4**, 372–74, **375**–401
  abiotic factors of, 376–77
  atmospheric oxygen in, 507
  biomes in, 380–93 (*see also* Biomes)
  distribution and significance of prokaryotes in, 299
  distribution of life in, 376
  effects of deforestation on carbon fixation in, 110
  energy flow in, 92–93 (*see also* Energy processing)
  evolutionary adaptations of organisms to environmental variability of, 378–79
  global climate change in, 372–73, 394–99 (*see also* Global climate change)
  as global ecosystem, 375
  human impacts on, 366, 374
  levels of life in, 4–8
  overview of ecology of, 374–75 (*see also* Ecology)
Biotechnology, **220**. *See also* DNA technology; Genetic engineering; Nanotechnology
Bioterrorism
  anthrax killer investigation, 231
  bacterial weapons in, 304
  smallpox vaccines and, 525
Biotic factors, **375**
  in biogeochemical cycles, 440
  in ecology, 375
Bipedalism, hominin, 364
Bipolar disorder, **586**
Birds, **359**
  adaptations of, to environmental variability, 378–79
  angiosperm pollination and dispersal by, 619, 621
  behavioral isolation and courtship rituals of, 272–73
  biological magnification and, 433
  characteristics and diversity of, 359
  cladistics and phylogenetic trees of, 288
  as descendents of dinosaurs, 284
  evolution of, by natural selection, 12–13
  evolution of ultraviolet vision in, 599
  extinctions of species of, 426
  finches (*see* Finches, Galápagos Islands)
  H1N1 influenza virus and, 173, 194
  interspecific competition and, 429
  population ecology and, 412
  predatory, 254
  as reptiles, 358–59
  wetlands and, 381
Birth canal (vagina), 555
Birth control pills, **560**. *See also* Contraception
Birth defects
  in IVF babies, 570
  spina bifida, 564
  trisomy 21 and Down syndrome, 139

Birth rates, 408, 410–11, 417
Bishop, J. Michael, 211
Bivalves, **343**
Black spider monkey, 362*f*
Blades, leaf, **609**
Blastocysts, 208, 210, 563, 565
Blastula, **338**
Bleeding, hemophilia and, 166
Bleeding, uterine, 558–59. *See also* Menstruation
Blindness
  genetically modified rice and, from vitamin A deficiency, 222
  glaucoma and, 589
  human gene therapy for progressive, 234
  retinitis pigmentosa and, 262
Blind spot, eye, 589
Blood, **459**. *See also* Red blood cells; White blood cells
  ABO blood groups of, 159, 503
  blood doping and, 101, 221, 495, 503–4
  blood pressure of, 455, 501
  bone marrow stem cells of, in leukemia treatment, 505
  cellular components of, 504*f*
  as connective tissue, 459
  defensive functions of white blood cells, 505
  flow of, through blood vessels, 500–502
  gene cloning of protein to dissolve blood clots in cardiovascular disease, 223*f*
  glucose homeostasis of, 465–66
  hemoglobin in (*see* Hemoglobin)
  hemophilia and, 166
  high-altitude athletic training and, 504
  in open and closed animal circulatory systems, 496–97
  oxygen transport by red blood cells, 503–4
  path of, in cardiovascular system, 497–98 (*see also* Cardiovascular systems)
  platelets and clotting of, 505
  pumping of, by heart, 499–500
  umbilical cord blood banking and, 210
  in urinary systems, 469–70
Blood flukes, 344
Blood pressure, 455, **501**
Blood vessels
  atherosclerosis and plaque in, 506
  blood flow through, 500–501
  blood flow through arteries, 501
  blood flow through capillary beds, 501–2
  blood flow through veins, 502
  in bones, 595
  in open and closed animal circulatory systems, 496–97
Blubber, thermoregulation and, 471
Blue cones, eye, 590
Blue-footed boobies, behavioral isolation of, 273
Blue whales, 360
Bodies, animal. *See* Animal structure and function
Body cavity, **340**–41*f*
Body cells. *See* Somatic cells
Body fat. *See* Fats, in adipose tissue
Body heat
  animal thermoregulation of, 467–68
  cellular respiration and, 78
  evolution of adaptations for thermoregulation of, 471
  human heat illnesses and, 454–55
Body mass index (BMI), **490**
Body plans
  animal, 340–41*f*
  annelid, 345
  arthropod, 347
  cnidarian, 342
  insect, 350
  mollusc, 343*f*
Body segmentation, **345**, 354
Bogs, 381
Boll weevil, 416
Bonds, chemical. *See* Chemical bonds
Bone marrow, 595
Bone marrow stem cells
  in human gene therapy, 234
  in leukemia treatment, 505
  lymphocytes and, 521
  red blood cells and, 503
Bones
  middle ear, 592–93
  skeletal system, 594–95
Bone tissue, **459**
Bony fishes, **356**
Booms, population growth, 411
Bordetela pertussis, 54
Bottleneck effect, 260–**61**
Botulism, 189, 301, 304
Bound ribosomes, 63
Bovine spongiform encephalopathy (BSE), 194
Brain, human, **582**–86. *See also* Brains
  breathing and, 511
  in central nervous system, 581–82
  cerebral cortex of, 584–85
  childhood cancer of, 212
  chimpanzee brain and, 364
  effects of drugs on, 580
  evolution of, 366
  hypothalamus and pituitary glands of, 540–41
  in integration of stimulus and response, 599
  magnetic resonance imaging (MRI) of, 31–32
  nervous tissue of, 461
  neurological disorders of, 586
  structure and function of, 583*t*
  temperature control centers in, 455, 467
  trauma to, 585
Brains
  ape, 362
  in central nervous systems, 576
  chimpanzee and human, 364
  human (*see* Brain, human)
  prions and diseases of, 194
Brainstem, **583**
Branching, 634
Branching, plant, 608
Brazil, Amazonian forest fragmentation in, 446
BRCA1 cancer gene, 213
Bread mold, 178
Bread wheat, sympatric speciation of, 276
Breast cancer
  inheritance of risk of, 213
  prevention and survival of, 129
  treatment of, with herceptin antibody, 522
Breathing, 94, 480, 507–**9**, 511. *See also* Respiratory systems
Breathing control centers, 511
Breeding. *See* Artificial selection; Captive breeding programs
Broccoli, artificial selection of, 13*f*
Broken bones, 595
Bronchi, **510**
Bronchioles, **510**
Bronchitis, 510
Brown algae, 310–11*f*
Brussels sprouts, artificial selection of, 13*f*
Bryophytes, **318**–20
Bubbles, DNA replication, 177*f*
Bubonic plague, 304
Buckeye butterfly, 351*f*
Budding, 328*f*, **552**
Buffers, pH and, **32**–33
Bulimia, **489**
Burgess Shale fossils, 339
Burmese pythons
  as invasive species, 414
  thermoregulation by, to warm eggs, 468
Busts, population growth, 411
Butterflies, effects of global climate change on, 396
Bypass surgery, 506

C

C_3 plants, **115**
C_4 plants, **116**
Cabbage, artificial selection of, 13*f*
Caenorhabditis elegans genome, 230
Caffeine, 580, 605
Calcitonin, **542**
Calcium (Ca)
  in composition of human bodies, 24
  in human diets, 488
  parathyroid glands and homeostasis of, 542
  therapy using, for osteoporosis, 595
Caloric balance, weight control and, 475, 485
Calorie (cal), **78**, **485**
Calories (C), food, 78, 485, 488
Calvin cycle, **110**, 115–16. *See also* Photosynthesis
Cambrian era, 282, 295, 339
Camouflage, predation and, 430
CAM plants, **116**
Cancer, **129**
  breast (*see* Breast cancer)
  carcinomas of epithelial tissue, 458
  as cell cycle disease, 128–29
  cervical, 129, 555, 561
  colon, 129, 212–13
  evolution of cells of, 215
  genetic basis of, 211–13
  Hodgkin's disease, 529
  inherited, 213
  leukemia, 210, 234, 505
  lung (*see* Lung cancer)
  mutagens as carcinogens, 187
  mutations causing pediatric brain, 212
  prostate, 129, 554
  radioactive isotopes and, 26
  risk and prevention of, 129, 214
  smoking and, 187, 198–99, 214, 513
  treatments for, 82, 129
  in United States, 214*t*
Canines. *See* Dogs
Canseco, Jose, 45*f*, 535
Cap, RNA, **182**
Capillaries, blood, **497**
  animal, 497
  blood flow through human, 498, 501–2
  in human urinary system, 469
  in respiratory system gas transport, 512
  tissues of, 500–501
Capillaries, lymphatic, 521
Capsules, prokaryotic cell, 58

Captive breeding programs
  for cheetahs, 261
  for Komodo dragons, 121
Carbohydrates, **40**. *See also* Sugars
  cellular respiration of, 100*f*
  chemical digestion of, 477
  as macromolecules, 39
  types of, 40–42
Carbon (C)
  biogeochemical cycling of, 441
  carbon chemistry of organic compounds, 38–39 (*see also* Biological molecules; Organic compounds)
  carbon footprints and, 398
  in composition of human bodies, 24
  in ecosystem chemical cycling, 437
  electron arrangement of electrons of, 26
  isotopes of, 26*t*
  nutritional modes and, 302
  radiometric dating using radioactive isotopes of, 282*f*
Carbon cycle, 441
Carbon dioxide (CO_2)
  animal exchange of oxygen and (*see* Cardiovascular systems; Circulatory systems; Respiratory systems)
  autotrophs and, 302
  in carbon cycle, 441
  carbon footprints and, 398
  in cellular respiration, 78, 94
  in chemical cycling between photosynthesis and cellular respiration, 92–93
  creation of sugar from, in Calvin cycle, 115
  fossil fuels and, 321
  as greenhouse gas, 395
  ocean acidification and, 33
  in photosynthesis, 108–10
  plant acquisition of, 626
  in redox reactions, 95
Carbon fixation, **110**
Carbon footprints, **398**. *See also* Greenhouse gases
Carboniferous period, 321
Carbon monoxide gas (CO), 512
Carboxyl groups, 46
Carcinogens, 187, **214**. *See also* Cancer
Carcinomas, 458. *See also* Cancer
Cardiac cycle, **499**
Cardiac muscle, **460**
Cardiovascular disease, **506**
  cholesterol and, 45
  gene cloning of protein to dissolve blood clots, 223*f*
  hypertension, 501
  saturated fats and, 44
  trans fats and, 16
  types of, 506
Cardiovascular systems, **496**–506
  athletic endurance and, 494–95, 504
  blood in, 503–5
  blood vessels in, 500–502
  cardiovascular fitness case study and, 31–32
  as closed circulatory systems, 496–97
  diseases of, 506 (*see also* Cardiovascular disease)
  heart function in, 499–500
  hormones in, 536
  path of blood in, 497–98
  respiratory systems and, 497–98, 509, 512 (*see also* Respiratory systems)
Carnivora order, phylogenetic tree for, 286*f*
Carnivores, **433**, **476**
Carotenoids, 112
Carpels, flower, 146, **324**, **617**
Carriers, recessive allele, **154**–56
Carrying capacity, **409**
  of human population, 419–20
  integrated pest management and, 416
  logistic population growth and limited, 409
  sustainable resource management and, 412–13
Cars, flexible-fuel, 107
Cartilage, **459**, 594–95
Cartilaginous fishes, **356**, 459
Case studies. *See also* Science
  on abiotic formation of biological monomers, 297
  on aerobic exercise and human brain size, 31–32
  on asexual reproduction of bdelloid rotifers, 137
  on biological control of kudzu, 415
  on dinosaur mass extinction by meteor impact, 284–85
  on DNA profiling of lung cancer patients, 233
  on drought and agricultural failure of Lost Colony of Roanoke, 616
  on effects of global climate change on species distribution, 396
  on effects of tropical forest fragmentation on biodiversity, 446
  on emergence of new senses, 598
  on engineering of enzymes, 81
  on ergot poisoning as cause of Salem witch, 331
  on evolution of lizard horn length as response to predation, 243
  on flu vaccines as protection for elderly humans, 192
  on genetic basis of coat variation in dogs, 157
  on genetic basis of lactose intolerance, 51
  on genetic basis of weight gain, 490–91
  on high-altitude athletic training, 504
  on HIV as cause of AIDS, 523
  on muscle fatigue as lactic acid accumulation from fermentation, 102
  on mutations causing childhood tumors, 212
  on phototropism and plant hormones, 633
  on python thermoregulation to warm eggs, 468
  on rage caused by steroids, 546
  on role of PSM protein in bacterial antibiotic-resistance, 61
  on trans fats, 15–16
  on using DNA profiling to identify viable IVF embryos, 569
  on wavelengths (colors) of light driving photosynthesis, 111
Casts, bone, 595
Cattle
  lactose tolerance and domestication of, 51
  methane from, 398
Cauliflower, artificial selection of, 13*f*
Celera Genomics, 230–33
Celiac disease, 484
Cell body, neuron, **576**
Cell-cell recognition, 83*f*
Cell cycle, eukaryotic, **125**
  cancer as disease of, 128–29
  chromosomes and, 123–25
  mitosis and cytokinesis in, 126–28
  phases of, 125
Cell cycle control system, **128**–29
Cell division, **122**. *See also* Cellular reproduction
  cell cycle of (*see* Cell cycle, eukaryotic)
  functions of, 122–23*f*
  in human embryonic development, 563–64
  mitosis vs. meiosis in, 134–35 (*see also* Meiosis; Mitosis)
  plant cytokinins and, 634
  in sexual and asexual reproduction by Komodo dragons, 121
Cell elongation, plant, 632–35
Cell junctions, **61**
Cell-mediated immune response, **526**–27
Cell plates, **128**
Cells, 54–73
  animal, 59*f*, 61, 338
  antibiotic-resistant bacteria and, 54–55, 61, 71
  case study on role of PSM protein in antibiotic-resistant bacteria, 61
  cellular respiration by (*see* Cellular respiration)
  cellular work of (*see* Cellular work)
  chemical composition of human, 24
  chloroplasts, mitochondria, and energy conversion in, 68
  cloning and genetic potential of, 207
  cytoskeletons of, 69–70
  digestion within, 478
  endomembrane systems of, 64–67
  formation of first pre-cells and, 298
  human skin, 74
  interstitial fluid of, 465
  as level of life, 5*f*, 7–8
  membrane proteins and shape of, 83*f*
  microscopes in study of, 56–57
  nuclei and ribosomes of, 62–63
  patterns of gene expression in differentiated, 200
  plant, 59*f*, 611–12
  plasma membrane structure of, 60–61
  prokaryotic vs. eukaryotic, 7–8, 58 (*see also* Eukaryotic cells; Prokaryotic cells)
  regulation of cellular differentiation of (*see* Gene regulation)
  replacement of, by cell division, 122
  reproduction of (*see* Cellular reproduction)
  size range of, 57*f*
  surfaces of, 61
  sympatric speciation and polyploid, 276
Cell signaling
  in gene regulation, 205
  membrane proteins in, 83*f*
  role of membranes in, 87
Cell theory, **56**
Cellular differentiation, **200**
Cellular reproduction, 120–43. *See also* Cells
  animal asexual reproduction by bdelloid rotifers and, 137
  cell cycle and mitosis in, 123–29
  functions of cell division in, 122–23*f*
  meiosis as basis of sexual reproduction, 130–40

sexual vs. asexual reproduction and, 120–21, 137, 140 (*see also* Asexual reproduction; Sexual reproduction)
Cellular respiration, 90–93, **94**–105
as aerobic harvest of food energy, 94
aerobic vs. anaerobic lifestyles and, 90–91, 102, 103
ATP in, 79–80
in chemical cycling, 92–93, 440–43
chemical energy and, 77–78
citric acid cycle in, 96, 98
electron transport in, 96, 99
emergence of, in history of life, 294
fermentation and lactic acid accumulation in human muscle fatigue, 102
fermentation vs., 101–3
glycolysis in, 96–97, 103
human food and, 485
human muscles and, 90–91, 102
by mitochondria, 68
overview of, 96
relationship between photosynthesis and, 109 (*see also* Photosynthesis)
resulting ATP yield from, 100
role of oxygen in, 95–96
simplified equation for, 94
three stages of, 96–99 (*see also* Cellular respiration)
Cellular slime molds, **309**
Cellular work, 74–89. *See also* Cells
ATP in, 79–80
cellular respiration (*see* Cellular respiration)
cellular structures and, 74–75
energy concepts and, 76–78
engineering artificial enzymes and, 81
enzymes in, 80–82
evolution of membranes in origin of life, 87
nanotechnology and, 75, 81, 87
plasma membrane function in, 83–87
Cellulose, **42**, 61, 611
Cellulosic ethanol, 107
Cell walls, **611**
fungal, 329
of plant cells, 42, 61, 317, 611–12
of prokaryotic cells, 58
Cenozoic era, 280–81*f*
Centipedes, **350**
Central dogma, gene expression process as, 178
Central nervous system (CNS), **576**, 581–82, 587. *See also* Brains; Nervous systems; Spinal cords
Central vacuoles, **67**, **611**
Centromeres, **125**
Centrosomes, **127**
Cephalopods, **343**
Cephalothorax, arthropod, 347*f*
Cerebellum, **583**
Cerebral cortex, **584**–85
Cerebral hemispheres, 584–85
Cerebrospinal fluid, **582**
Cerebrum, 583–**84**
Cervical cancer, 129, 555, 561
Cervix, **555**
CFCs (chlorofluorocarbons), 394
Chaparral vegetation, **388**
Characters, heritable, **146**
law of independent assortment and, 150–51
law of segregation and, 147–49
traits vs., 146 (*see also* Traits)
Charophytes, **318**
Cheatgrass, as invasive species, 413–14
Cheddar Man, DNA profiling of, 227
Cheese, lactose intolerance and, 37
Cheetahs, bottleneck effect on, 261
Chemical bonds, **27**
activation energy and, 80
in DNA, 50
types of, 27–28
Chemical cycling, **437**, 440–43
biogeochemical cycles and abiotic reservoirs in, 440
carbon cycle in, 441
energy flow and, in ecosystems, 6, 437 (*see also* Energy flow)
nitrogen cycle in, 442
nutrient pollution and, 443
phosphorus cycle in, 441
prokaryotes and, 299, 305
Chemical digestion, 477, 482
Chemical energy, **77**. *See also* Energy processing
cellular work and, 77–78
chemotrophs and, 302
conversions of, by chloroplasts and mitochondria, 68
conversions of solar energy to, by light reactions, 110–14
in ecosystem energy flow, 437–39
in ecosystems, 6
photosynthesis and, 108
Chemical evolution, origin of life in, 296–98
Chemical reactions, **28**
blood and interstitial fluid chemical exchange, 502
cellular work and, 79
chemical energy and, 77–78
chemical work and, 79*f*
electron arrangements and, 26
metabolism, enzymes, and, 80–82
reactants and products of, 28
role of functional groups in, 38–39
Chemicals
chemoreceptors of, 588
as defenses, 430–31
DNA damage from toxic, 177
ecosystem chemical cycling of (*see* Chemical cycling)
as mutagens, 187
in nutrient pollution, 443
in water pollution, 391
Chemical synapses, 579–80
Chemistry, 22–35
atoms in, 25–26
case study on effect of aerobic exercise on human brain size, 31–32
chemical bonding of molecules in, 27–28
chemical reactions in, 28
elements, compounds, and composition of matter in, 24–25
of water, 22–23, 29–33 (*see also* Water)
Chemoheterotrophs, 302, 329
Chemoreceptors, **588**
Chemosynthetic prokaryotes, 432
Chemotherapy, cancer, **129**, 233, 505
Chemotrophs, 302
Chernobyl nuclear reactor explosion, 26
Chestnut blight, 432
Chewing, 477, 479
Chiasma, **136**
Chicken pox virus, 190, 525
Chicken virus, cancer-causing, 211
Chicxulub meteor crater, 284*f*–85
Childbirth, 568
Childhood tumors, mutations causing, 212
Childhood vaccination, 525
Chimpanzees
evolutionary relationship of humans and, 363
evolution of, 361*f*–63
genome of, 232
Jane Goodall's observations of, 14*f*
and paedomorphosis in human skulls, 279
Chinese river dolphins, extinction of, 426*f*
Chlamydia, **560**–61*f*
Chlamydomonas, 310
Chlorofluorocarbons (CFCs), 394
Chlorophyll, **108**
in chloroplasts, 108, 112
in light reactions, 110
in photosystem reaction centers, 113
relative abundance of, and global photosynthesis, 376
Chlorophyll *a* pigment, **112**
Chlorophyll *b* pigment, 112
Chloroplasts, **68**, **108**, **611**
emergence of, in history of life, 294
evolution of, from symbiotic prokaryotes, 306
light reactions in, 110–14
in plant cells, 59
as sites of photosynthesis, 68, 108–9*f*, 611
Chloroquine, 243
Choanocytes, 341
Chocolate, saturated fatty acids in, 44
Choking, 510
Cholera, 221, 483
Cholesterol
cardiovascular disease and, 506
hypercholesterolemia and, 158
as steroid, 45
Chordates (Chordata), **354**–55. *See also* Vertebrates
Chorion, **565**
Chorionic villi, **565**
Chorionic villus sampling, 157
Choroid, 589
Chromatin, **62**, **123**–24. *See also* Chromosomes
Chromosomal basis of inheritance, 162–67
canine evolutionary tree and, 167
chromosome theory of inheritance and, 162
genetic recombination in crossing over and, 163–64
linkage maps and, 164
linked genes and, 163
sex-linked genes and, 165–66
Chromosome theory of inheritance, **162**. *See also* Chromosomal basis of inheritance
Chromosomes, **58**, **122**
autosomes, 131
in cell division, 122–25
chromatin and, 62
crossing over between, 136–37
DNA in, 49–50, 58
eukaryotic, 123–25
genetic variation from independent assortment of, 135–36, 258
homologous, in sexual reproduction, 130–31
inheritance and (*see* Chromosomal basis of inheritance)
law of segregation and homologous, 149

Chromosomes (*Continued*)
nondisjunction errors and abnormal numbers of, 138–40
number of, in cells of mammals, 123*f*
sex (*see* Sex chromosomes)
Chronic wasting disease, 194
Chrysanthemums, 636
Chyme, **480**, 482
Cichlid fish, 547
Cigarettes. *See* Smoking
Cilia, **70**
cell movement and, 70
effects of smoking on, 513
human throat, 54
mucus and, 518
Ciliates, **308**–9*f*
Cinnamon, as herbivory defense, 431
Ciprofloxacin, 55
Circulatory systems, **496**. *See also* Respiratory systems
human and vertebrate (*see* Cardiovascular systems)
open and closed, 496–97
structure and function of respiratory surfaces in, 507–8
vertebrate, 462*f*
Circumcision, 554
Citric acid cycle, **96**, 98, 100
Clades, **287**–88
Cladistics, **287**–88
Clams, 343
Classes (taxonomy), **286**
Classification. *See* Systematics
Cleavage, **563**–64
Cleavage furrows, **128**
Climates
effects of, on terrestrial biome distribution, 384–85
evolution of alternative photosynthetic pathways for, 116
global changes of (*see* Global climate change)
tree ring data on, 615–16
Climographs, 386
Clinton, Bill, 226
Clitoris, **555**
Clonal selection, **524**
Clones, **223**–24
Cloning, 207–10
plant, 207
reproductive, of animals, 208–9
therapeutic, and stem cells, 210
Closed circulatory systems, **496**–97
Clostridium botulinum, 301, 304
Clotting, blood, 505
Cloves, as herbivory defense, 431
Clutch size, 410
Cnidarians (Cnidaria), **342**, 382
Cnidocytes, 342
Coal, 321
Coastal marshes, ecosystem services of, 424–25
Cocaine, 580
Cocci, **300**
Cochlea, **592**–93
Cochlear implants, 593
Cocoa butter, saturated fatty acids in, 44
Codeine, 580
CODIS (Combined DNA Index System) database, 228
Codominant alleles, **159**
Codon recognition, **184**
Codons, **179**–80, 184
Coelacanth, 356
Coelom, **340**–41*f*
Coenzyme A (CoA), 98
Coffee plants, 604–5
Cohesion, **29**, **629**–30
Cold-blooded animals, reptiles as, 358
Cold sore virus, 191
Cold weather adaptations, 378
Collagen, 459
Collecting ducts, urinary system, 469
Collenchyma cells, **612**
Colon, **484**
Colon cancer, 129, 212–13
Colonial algae, 310–11
Colonial slime molds, 309
Colony collapse disorder, bee, 621
Coloration, predation and adaptive, 430
Colorblindness, 165–66, 590
Colors
adaptive coloration and, 430
wavelengths of visible light as, 111
Colostrum, 568
Combined DNA Index System (CODIS) database, 228
Common ancestors, cladistics and, 287–88
Common box turtle, 358*f*
Common cold virus, 190
Communities, **375**, **428**
community ecology and, 375, 428 (*see also* Community ecology)
in freshwater biomes, 380
as level of life, 5*f*
lionfish as threats to coral reef, 402–3
in terrestrial biomes, 385–86
Community ecology, **375**, 428–37
communities in, 375, 428 (*see also* Communities)
community disturbances in, 436
ecological succession in, 436–37
interspecific interactions in, 428–32
species diversity in, 435
trophic structure in, 432–34
Comparative anatomy, **250**
Comparative embryology, 251
Competition
evolution by natural selection and, 11, 252–53, 262–63
interspecific, 429
sexual selection and, 264
Competitive exclusion principle, **429**
Complementary DNA (cDNA), **207**, 225
Complement proteins, **519**
Complete digestive tracts, **345**
Compost, **627**
decomposers in, 433
organic fertilizers and, 627
Compound leaves, 609
Compounds, **25**. *See also* Molecules
carbon-based organic, 38–39 (*see also* Biological molecules)
as combinations of elements, 25
ionic bonds and ionic, 27
Computer model, DNA, 176*f*
Concentration gradients, passive transport and, **84**
Conception, 562. *See also* Fertilization
Condums, **560**–61
Cones, gymnosperm, 323
Cones, retinal, **590**
Coniferous forests, **389**
characteristics of, **389**
climate and, 385
human impacts on, 392
in temperate zones, 384
Conifers, **319**, 322–23, 389
Conjunctiva and conjunctivitis, 589
Connective tissue, **458**–59, 500–501, 595
Conservation biology, **444**–49
biodiversity hot spots in, 444
biophilia and, 448
captive breeding programs, 121, 261
case study on effects of tropical forest deforestation on biodiversity, 446
endangered and threatened species and (*see* Endangered species; Threatened species)
landscape ecology in, 445
restoration ecology in, 444, 447
sustainable development and, 448
Conservation of energy, **76**
Constipation, 484
Consumers, **92**, **432**
animals as, 9
in chemical cycling, 440–43
in ecosystem energy flow and chemical cycling, 437
in ecosystems, 6
producers vs., 92 (*see also* Producers)
in trophic structure food chains, 432–33
in trophic structure food webs, 434
Contact lenses, 591
Continental drift, macroevolution and, 283
Continental shelves, 382
Contraband animal products, DNA profiling and, 226
Contraception, **559**–60
Contractile proteins, 46*f*
Contractile vacuoles, 67
Contraction, muscle, 596–98
Control groups, 16
Controlled experiments, scientific, **16**. *See also* Case studies; Science
Convergent evolution, **287**
in differing terrestrial biomes, 385–86
homologies vs. analogies and, 286–87
Coral reefs, **382**
Cnidarians and, 342
energy flow in, 438
lionfish as threats to communities of, 402–3
loss of biodiversity of, 427
in marine biomes, 382–83*f*
mutualism of coral polyps and algae in, 430
protists and, 307
Coral snakes, mimicry in, 430–31*f*
Cork, **616**
Cork cambium, **616**
Corn
food energy for humans from, 439
genetically modified, 221
Cornea, **589**
Coronary arteries, 498, **506**
Corpus callosum, **584**
Corpus luteum, **555**, 557
Cortex, plant, **610**, 616
Corticosteroids, **545**
Cortisone, 545
Costa Rica, 396
Cotton plants, hybrid breakdown of, 273
Cotyledons, **606**
Courtship rituals, 272–73
Covalent bonds, **27**–28
Crabs, 349*f*
Cranium, 354
Crayfish, 349*f*
Creosote bushes, asexual reproduction of, 617*f*
Cretaceous mass extinction, 284
Creutzfeldt-Jakob disease, 194
Crick, Francis, 175*f*
central dogma concept of, 178
discovery of structure of DNA by, 17, 175–77

Crime scene investigation. *See* Forensics
Cristae, mitochondrial, **68**
Crocodiles, 358–59*f*
Crohn's disease, 484, 529
Crop rotation, 629
Crops. *See also* Agriculture; Food
  angiosperms as, 605–6
  annuals as, 613
  genetically modified (GM) (*see* Genetically modified (GM) organisms)
  integrated pest management and, 416
  photosynthetic pathways of, 115–16
  sympatric speciation and, 276
Crosses, genetic, **147**
  cross-fertilizations as, 147
  dihybrid, 150–51
  monohybrid, 148–49
  testcrosses, 152
Crossing over, **136**
  genetic recombination as, 163–64
  genetic variation from, 136–37, 258
  in meiosis, 132–33
Crustaceans, 347*f*, **349**
Cryptic coloration, **430**
Culture, **366**
Cuticle, 316*f*, **317**, **610**
Cyanide, electron transport and, 99
Cyanobacteria, 108*f*, 300*f*, 443
Cystic fibrosis (CF), **155**
Cytokinesis, **125**
  meiosis and, 133*f*
  mitosis and, 125, 127*f*–28
  plant cytokinins and, 634
Cytokinins, **634**
Cytoplasm, **59**
  cytoskeletons of, 69–70
  of eukaryotic cells, 59
  ribosomes in, 63
Cytosine (C), 7, 49–50, 174–**75**
Cytoskeletons, **69**–70, 83*f*
Cytosol, **58**, 63
Cytotoxic T cells, **527**

D

Dams, flooding and, 381
Darwin, Charles
  cultural and scientific context of, 245–47
  descent with modification theory of, 244, 247
  on earthworms, 345
  as ecologist, 378
  Gregor Mendel and, 256
  observations of, on biodiversity of species, 270
  study by, of chemical signals (hormones) in plant phototropism, 633
  on systematics, 289
  theory by, of evolution by natural selection, 10–13, 244–45 (*see also* Evolution; Natural selection)
  on voyage of the *Beagle*, 246–47
Darwin, Francis, 633
Darwinism, synthesis of Mendelism and. *See* Modern synthesis
Dating methods, fossil, 270, 282
Daughter DNA molecules, 177
Day vision, 590
DDT
  biological magnification of, 433
  insect resistance to, 243, 253
Dead zone, Gulf of Mexico, 443
Deafness, 154–55, 593
Death rates. *See also* Mortality
  cardiovascular disease, 506
  human population growth and, 417
  population growth and, 408, 410–11
  survivorship and, 406–7
Deciduous trees, 389
Decomposers, **433**
  in chemical cycling, 440–43
  in ecosystem energy flow and chemical cycling, 437, 440
  in ecosystems, 6
  fungi as, 9, 330
  prokaryotes as, 299, 305
  roundworms as, 346
  slime molds as, 309
  in trophic structure food chains, 433
Deep-sea hydrothermal vents, 297, 299*f*, 376, 382–83
Deepwater Horizon oil spill, 383
Defeng, Yao, 541*f*
Defensive proteins, internal innate defense of, 519–20
Defibrillators, 500
Deforestation
  effects of, on biosphere carbon fixation, 110
  effects of, on cycling of carbon dioxide, 395
  effects of, on forest biomes, 392
  loss of plant diversity by, 327
Dehydration
  animal osmoregulation and, 469
  animal water balance and, 85
  diarrhea and, 484
  diuretics and, 470, 540
  human heat illnesses and, 455
Dehydration reactions, **39**
  formation of polymers from monomers by, 39
  formation of polynucleotides by, 50
  formation of proteins by, 47
  formation of triglycerides by, 43
Dementia, 586. *See also* Alzheimer's disease
Denaturation, of protein, **48**
Dendrites, **576**
Denitrifying bacteria, 442
Density, population. *See* Population density
Density-dependent factors, population growth, **410**
Density-independent factors, population growth, **411**
Dental plaque, 301
Deoxyribose, DNA and, 49–50, 175
Deposit feeders, 382–83
Depressive illness, 580, 586
Dermal tissue system, **610**–11
Dermis, 458
Descent with modification theory, 10, 244, 247. *See also* Evolution; Natural selection
Deserts, **387**
  characteristics of, 387
  effects of global climate change on, 397
  food webs in, 434
  solar energy and, 384
Designer steroids, athletic abuse of, 45, 534–35, 546
Detergents, phosphate pollution by, 443
Determinate growth, animal, **613**
Detoxification. *See also* Toxins
  phytoremediation and bioremediation as, 624–25 (*see also* Bioremediation)
  smooth ER and, 65
Detritivores, **433**, 437
Detritus, **433**
Development
  embryonic (*see* Embryonic development)
  evo-devo and macroevolution by processes of, 279
  human developmental abnormalities, 565
  plant (*see* Plant growth)
  as property of life, 4
Development, economic. *See* Economic development
Diabetes mellitus (diabetes), **544**
  as autoimmune disease, 529
  genetic engineering of insulin for, 8, 220–21
  glucose homeostasis and, 100, 465
  pancreas hormones and, 544
Dialysis, **470**
Diaphragm, respiratory system, **510**–11
Diaphragms, contraceptive, **560**
Diarrhea, 308, 484
Diastole, **499**, 501
Diatomaceous earth, 310
Diatoms, **310**
Diazepam, 580
Dicots, **606**
Dietary fats
  hydrocarbons in, 38–39*f*
  saturated and unsaturated fatty acids, 43–44
  trans fats, 15–16
Dietary fiber, 42
Diets. *See also* Food; Nutrition, animal
  animal, 476
  animal nutrition and, 476–78
  cancer prevention or survival and, 129, 214
  cardiovascular disease and, 506
  essential amino acids for vegetarian, 486
  evolution of human fat and sugar cravings, 491
  fats in (*see* Dietary fats)
  fiber in, 42
  human nutritional requirements and, 485–88 (*see also* Nutrition, human)
  human weight control and, 474–75
  lactose intolerance and human, 36–37, 51
  nutritional disorders and, 489–91
  trace elements in human, 24–25*f*
Diffusion, **83**, **496**
  animal circulation by, 496
  passive transport as, 83–84
  water balance and osmosis as, 84–85
Digestion, **476**. *See also* Digestive systems
  animal nutrition and, 476–78
  human, 484*f*
  of lactose (*see* Lactose intolerance)
  by lysosome enzymes, 66
  of polymers, 39
  of polysaccharides, 42
Digestive system, human, 479–84. *See also* Digestive systems
  esophagus in, 480
  large intestine in, 484
  mouth in, 479
  pharynx in, 480
  small intestine in, 482–83
  stomach in, 480–81
  system map of, 479

Digestive systems
digestive compartments of animal, 478
in exchanges with external environments, 465
human (*see* Digestive system, human)
vertebrate, 462*f*
Digestive tract, **478**
Dihybrid crosses, **150**–51
Dilation stage, labor, 568
Dinklage, Peter, 541*f*
Dinosaurs
birds as, 359
mass extinction of, 284–85, 289, 358
as reptiles, 358–59*f*
Diphtheria, 189
Diploid organisms, **131**
Diptheria/pertussis/tetanus (DPT) vaccination, 525
Directed evolution, engineering of enzymes by, 81
Directional selection, **263**
Disaccharides, **41**
Disasters
bottleneck effect of, 260–61
nuclear, 26, 624–25
Discovery science, **14**, 374. *See also* Science
Diseases, animal
prion infections, 194
viral infections, 190–91
Diseases, plant fungal, 330
Diseases and disorders, human. *See also* Medicine
abnormal numbers of sex chromosomes and, 139–40
achondroplasia, 156
alkaptonuria, 178
Alzheimer's disease, 48, 231, 586
anemia, 221, 503, 505, 512
antibiotic-resistant bacteria and (*see* Antibiotic-resistant bacteria)
atherosclerosis, 44, 500
bacterial, 299, 301, 303–4
birth defects, 139, 564, 570
blindness (*see* Blindness)
blood clotting and, 505
botulism, 301
brain trauma, 585
cancer (*see* Cancer)
cardiovascular disease (*see* Cardiovascular disease)
central nervous system, 581–82
cholera, 221
cystic fibrosis (CF), 155
deafness, 154–55
developmental abnormalities, 565
diabetes (*see* Diabetes mellitus (diabetes))
dwarfism, 236
fever in, 467
fungal, 330
genetic, 154–57, 165–66
goiter, 24–25*f*
H1N1 influenza virus, 172–73
hearing problems, 592–93
heart attacks, 500–501, 505–6
heart murmurs, 499
heat illnesses, 454–55
hemophilia, 166
hepatitis B, 221
hormonal, 541–42, 544
human-caused disturbances and emerging, 436
human genome and genes for, 231
Huntington's disease, 156
hypercholesterolemia, 158
hypertension, 501
immune system (*see* Immune disorders)
infertility (*see* Reproductive technologies)
influenza viruses, 172–73
insects as carriers of, 352
kidney failure, 470
lactose intolerance, 36–37, 51
of large intestine, 484
leukemia, 210, 234, 505
lysosomal storage diseases, 66
malaria, 242–43, 265
mineral deficiencies, 488
misfolded proteins and, 48
multiple sclerosis, 577
muscular dystrophy, 165
neurological disorders, 586
neurotransmitter disorders, 580
nutritional, 489–91
obesity and, 475, 490
parasitic flatworms and, 344
parasitic roundworms and, 346
Parkinson's disease, 231
phenylketonuria (PKU), 259
pneumonia and meningitis, 230
prions and Creutzfeldt-Jakob disease, 194
protists and, 307, 308
radioactive isotopes and, 26
recessive genetic, 154–56
red-green colorblindness, 165–66
respiratory system, 510
retinitis pigmentosa, 262
severe combined immunodeficiency disease (SCID), 234
sexually transmitted diseases (STDs), 560–61
sickle-cell disease, 47, 160, 186, 265
skeletal diseases and injuries, 595
of small intestine, 483
stomach ailments, 481
thalassemias, 265
trans fats and, 15–16
trisomy 21 and Down syndrome, 139
viral, 188*f*–89, 190–94
vision problems, 589, 590, 591
vitamin deficiencies, 487
Dishwasher detergents, phosphate pollution by, 443
Disorder, bee colony collapse, 621
Dispersal, fruit and seed, 326*f*, 619
Disruptive selection, **263**
Distance vision, 589*f*
Distribution, geographic. *See* Geographic distribution of species
Disturbances, **436**
as abiotic factors, 377
community ecology and, 436
ecological succession after, 436–37
at ecosystem edges, 445
population growth and, 408, 411
Diuretics, 470, 540
Diversity, biological. *See* Biodiversity
Dizygotic twins, 563
DNA (deoxyribonucleic acid), **49**, 172–74, **175**–97
analysis of Neanderthal, 365
in case study on effects of flu vaccines on elderly humans, 192
as chemical material of genes, 7–8 (*see also* Genes)
in chloroplasts and mitochondria, 68
chromosomes of, in cell division, 122
deadly viruses and, 172–73, 192, 194
discovery of structure of, 17, 175–77
in eukaryotic chromosomes, 123–25
in eukaryotic nuclei, 62
as evidence of evolution, 251
flow of genetic information from, to RNA and proteins, 63, 178–87 (*see also* Gene expression)
genetic code of, for amino acids, 179–80
H1N1 influenza virus and, 172–73
in human embryonic development, 563–64
models representing structure of, 176*f*
in molecular systematics, 287
noncoding, 182, 228, 230–31
as nucleic acid, 49–50
in prokaryotic reproduction, 301
repair of damage to, 177
replication of, 177
structure of, 17, 50, 174–77
technologies of, 17–18 (*see also* Biotechnology; DNA technology; Genetic engineering)
transcription of, to RNA, 181
transplanting of, 180
unity in diversity of life and, 9
in viruses and other noncellular infectious agents, 188–94
DNA ligase, **224**
DNA microarrays, **206**
identifying viable IVF embryos using, 569
visualizing gene expression with, 206–7
DNA packing
in cell division, 124
gene regulation of, 202–3*f*
DNA polymerases, **177**
in automated polymerase chain reaction, 227
in DNA replication, 177
DNA probes, selecting genes in genomic libraries using, 224–25
DNA profiling, **226**
applications of, 226–27
ethical issues on, 236–37
in forensics, 17, 218–19, 226, 228
gel electrophoresis in, 228–29
identifying viable IVF embryos using, 569
of lung cancer patients, 233
polymerase chain reaction (PCR) in, 227
restriction fragment length polymorphism (RFLP) analysis in, 228–29
short tandem repeat (STR) analysis in, 228
techniques of, 227–29
DNA strands, polynucleotides as, 50
DNA synthesizers, 225
DNA technology, **220**–40. *See also* Genetic engineering
biotechnology and, 220
DNA profiling (*see* DNA profiling)
genetic code and, 180
genomics, 230–33
human gene therapy, 234
proteomics, 233
recombinant DNA technology, 220–25
safety and ethical issues of, 235–37
Dogs
artificial selection of, 12–13*f*
breeding of, by humans, 144–45, 151, 156, 167
evolution of, 167
genetic basis of coat variation in, 157
Dolly (sheep), 208–9

Dolphins
  extinction of Chinese river dolphin, 426*f*
  as mammals, 360
Domains (taxonomy), 9, **286**. *See also* Archaea domain; Bacteria domain; Eukarya domain
Dominant alleles, **148**
  human genetic disorders and, 156
  recessive alleles vs., 148
Dominant traits, 153–54
Donne, John, 397
Dopamine, 580
Dormancy, seed, 619, 620, 635
Dorsal, hollow nerve cord, **354**
Double bonds, 27*f*, 38*f*
Double circulatory systems, **497**–98. *See also* Cardiovascular systems
Double fertilization, **325**, **619**
Double helix, DNA, **50**, **175**–77. *See also* DNA (deoxyribonucleic acid)
Doubly compound leaves, 609
Down, John Langdon, 139
Down syndrome, **139**
Drosophila melanogaster (fruit fly). *See* Fruit flies (*Drosophila melanogaster)*
Drought, 22–23, 616
Drugs. *See also* Medicine
  antibiotic (*see* Antibiotics)
  anticoagulant, 505
  antidepressant, 586
  antihistamine, 528
  anti-HIV and anti-AIDS, 193, 530
  anti-inflammatory, 520, 595
  anti-malaria, 243
  cardiovascular disease and, 506
  chemotherapy, for cancer, 129, 233
  diuretic, 470, 540
  effects of, on fetal development, 565
  effects of, on human brain, 580
  effects of, on sensory receptors, 588
  as enzyme inhibitors, 82
  fungi and, 332
  impact of loss of plant diversity on production of, 327
  infertility, 569
  reproductive cloning for, 208–9*f*
  smooth ER and tolerance of, or addiction to, 65
Dry fruits, 620
Dual reproductive capabilities, 553
Duck-billed playtpus, 360*f*
Duodenum, **482**
Dust bowl, American, 23
Dutch elm disease fungus, 330*f*
Dwarfism (achondroplasia), 156, 236, 541

E

Eagles, 359
Ear, 592–93
Eardrum, **592**–93
Earth. *See* Biosphere
Earth history, macroevolution and, 280–85, 294–95. *See also* Macroevolution
Earthquakes, 283*f*
Earthworms, **345**, 478, 507–8*f*, 553
Ear wax, 518
Eastern coral snakes, mimicry in, 430–31*f*
Eating. *See also* Food; Nutrition, animal; Nutrition, human; Nutritional modes; Trophic structures
  human eating disorders, 489
  as nutritional mode, 338
Eat Lionfish campaign, 403
Ebola virus, human-caused disturbances and, 436
Echidna, 360
Echinoderms (Echinodermata), **353**
Echolocation, 575
E. coli bacteria
  bacteriophages and, 188–89
  genome of, 230
  in human large intestine, 484
  lac operon and, 201
Ecological footprints, **419**–20
Ecological niches, **429**
Ecological Society of America, 448
Ecological succession, **436**–37
Ecology, **374**
  environmentalism and, 374
  evolutionary biology and, 378
  hierarchy of interactions and fields of, 375
  landscape ecology, 445
  overview of, 374–75
  restoration ecology, 444, 447
Economic development
  age structures and, 417–19
  deforestation for, 392
  goal of sustainable, 448
  value of ecosystem services for, 425
Ecosystem diversity, 427
Ecosystem ecology, **375**, 437–43
  chemical cycling in, 437, 440–43
  ecosystems in, 375, 437 (*see also* Ecosystems)
  energy flow in, 437–39
Ecosystems, **6**, **375**, 424–36, **437**–52. *See also* Environments
  biodiversity of, 424–28, 446, 448–49
  community ecology and, 428–37 (*see also* Community ecology)
  conservation biology, restoration ecology, and, 444–49 (*see also* Conservation biology)
  ecosystem ecology and, 375, 437–43 (*see also* Ecosystem ecology)
  effects of deforestation on carbon fixation in, 110
  effects of global climate change on, 397
  effects of tropical forest deforestation on biodiversity of, 446
  evolution of biophilia and, 448–49
  fungal impact on, 330–32
  as level of life, 5*f*–6
  loss of natural, 425, 427
  nutritional modes in, 6, 92
  primary production of different, 438*f*
  prokaryotic impact in, 305
  services of, 424–25, 427
Ecosystem services, **427**
  of forests, 392
  loss of biodiversity and loss of, 424–25
  loss of natural ecosystems and loss of, 427
Ectoderm, 340, 563
Ectopic pregnancy, 563
Ectotherms, **358**–59, **467**–68
Edges, ecosystem, 445–46
Effector cells, **524**, 526, **576**
EGFR gene, chemotherapy and, 233
Egg cells, plant
  in flower carpels, 146
  in gametangia, 317
Eggs, **553**
  amniotic, 355*f*, 358
  amphibian, 357
  angiosperm, 617, 618
  egg-laying mammals and, 360
  as female gametes in sexual reproduction, 122, 131, 553
  gametic isolation and, 273
  human, 165, 555–57, 562
  human infertility and, 568–69
Einkorn wheat, 426*f*
Eisner, Thomas, 352
Ejaculation, **554**
Electrical synapses, 579
Electrocardiogram (ECG or EKG), **500**
Electromagnetic receptors, **588**
Electromagnetic spectrum, **110**–11
Electron configurations, 27*f*
Electron microscope (EM), **56**–57
Electrons, **25**
  in cellular respiration, 95–96
  in fermentation, 101
  in organic compounds, 38
  in photosynthesis, 109
  states of, in chloroplast pigments, 112
  structure and properties of atoms and arrangement of, 25–26
Electron transport, **96**, 99–100
Electron transport chains, **95**
  in cellular respiration, 95–96
  in light reactions, 114
Electroreception, 356, 575, 598
Elements, **24**–26
Elephants
  DNA profiling and poaching of, 226
  seismic sense of, 574–75, 588, 592
Elephant seals, male aggression in, 547
Elimination, **476**, 484
Elm trees, 330
Elongation, plant
  hormones and, 632–35
  primary growth and, 613–14
Elongation phase, transcription, 181
Elongation phase, translation, 184
Embolus, 505
Embryology, comparative, 251
Embryonic development
  evidence of evolution in comparative, 251
  homeotic genes in gene regulation of, 205–6
  homologies in, 287
  human (*see* Human embryonic development)
  lysosome functions in, 66
  plant, 317
Embryonic stem cells (ES cells), therapeutic cloning using, **210**. *See also* Stem cells
Embryos, **555**
  development of (*see* Embryonic development)
  seeds as plant, 317, 319, 618–19
  using DNA profiling to identify viable IVF, 569
  zygotes vs., 555
Embryo sacs, angiosperm, **618**–19
Emergent properties, 4
Emerging viruses, **194**, 436
Emotions, 546, 583
Emphysema, 510
Endangered species, **412**. *See also* Threatened species
  in biodiversity hot spots, 444
  blue whales, 360
  population ecology and, 404, 412
  reproductive cloning to preserve, 208–9*f*
  sixth mass extinction and, 268–69
  species diversity and, 426

Endangered Species Act, 412
Endemic species, **444**
Endocrine glands, **536**. *See also* Endocrine systems
Endocrine systems, 534–35, **536**–49
  adrenal glands of, 544–45
  athletic steroid abuse and, 534–35, 546–47
  evolution of steroids of, and male aggression, 547
  glands of, 538–39*t*
  gonads of, 546
  hormones of, 536–37
  hypothalamus and pituitary glands of, 540–41
  pancreas of, 543–44
  thyroid and parathyroid glands of, 541–42
  vertebrate, 463*f*
Endocytosis, **86**, 341
Endoderm, 340, 563
Endodermis, plant, **610**
Endomembrane systems, **64**–67
  endoplasmic reticulum in, 64–65
  evolution of eukaryotic, from prokaryotic, 306
  Golgi apparatus in, 65
  lysosomes in, 66
  vacuoles in, 67
Endometrium, **555**, 558–59, 565
Endoplasmic reticulum (ER), **64**
  attachment of ribosomes to, 63
  functions of rough and smooth, 64–65
Endorphins, **541**, 580
Endoskeletons, **353**–54, **594**
Endosperm, **325**, **619**
Endospores, **301**
Endosymbiosis, **306**
Endotherms, **359**, 467
Endotoxins, **303**
Endurance, athletic, 494–95, 504, 513
Energy, **76**–78
  as abiotic factor in biosphere, 376
  in adipose tissue, 459
  biofuels as green (*see* Biofuels)
  carbon footprints and consumption of, 398
  chemical, 77–78 (*see also* Chemical energy)
  conservation of, and types of, 76
  entropy and, 77
  flow of, in biosphere, 92–93 (*see also* Energy processing)
  flow of, in ecosystems, 437–39
  food calories and, 78
  mechanoreceptors and mechanical, 588
  in neurons, 577–78
  nutritional modes and, 302
  sensory receptors of electromagnetic, 588
Energy flow, **437**–39
  chemical cycling and, in ecosystems, 6, 437 (*see also* Chemical cycling)
  ecological pyramids of production in, 438–39
  human resource use and, 439
  primary production and energy budgets in, 438
Energy processing. *See also* Cellular respiration; Chemical energy; Photosynthesis
  cellular (*see* Cellular work)
  chemical cycling between photosynthesis and cellular respiration in, 92–93
  by chloroplasts and mitochondria in cells, 68
  in ecosystems, 6
  producers vs. consumers in, 92
  as property of life, 4
Engelmann, Theodor, 111
Engineering, genetic. *See* Genetic engineering
Enhancers, DNA, **203**
Entropy, energy conversions and, **77**
Environmentalism, ecology and, 374. *See also* Conservation biology; Ecology
Environmental Protection Agency (EPA), 236
Environments. *See also* Biomes; Ecosystems
  abiotic factors in, 376–77
  animal exchanges with external, 464–65
  animal regulation of internal, 465–71 (*see also* Homeostatic regulation)
  carrying capacities of, 409
  Charles Darwin's observations of ways organisms are suited to, 244
  effects of deforestation on carbon fixation in, 110
  evolutionary adaptation to, by organisms, 11–13, 244–45
  evolution by natural selection and adaptation of species to, 11–13
  exponential population growth and unlimited, 408
  human impacts on, 374
  impacts of technology on, 18
  logistic population growth and limited, 409
  response to, as property of life, 4–5*f*
  role of, in inheritance, 161
  sensitivity of protein shape to, 48
  significance of prokaryotes to health of, 299
Enzyme inhibitors, **82**
Enzymes, **80**–82
  in cellular work, 80–82
  chemical digestion by, 477
  cutting and pasting DNA using, 224
  digestive, in lysosomes, 66
  in DNA replication, 177
  fungal digestive, 329
  in gene expression, 178
  human digestive, 480–82
  inhibitors of, 82
  membrane proteins as, 83*f*
  nanotechnology, glycolysis, and, 75
  nanotechnology and engineering of, 81
  proteases, 193
  as proteins, 37, 46*f*
  reverse transcriptase, 192–93
Epidemiologists, 192
Epidermis, human, 458, 563
Epidermis, plant, 610, 616
Epididymis, 554, 556
Epiglottis, 480
Epinephrine (adrenaline), **544**
  adrenal gland production of, 544–45
  for anaphylactic shock, 528
  autonomic nervous system and, 582
  in cell signaling, 87
  human heart pacemaker and, 500
  as neurotransmitter, 580
Epithelial tissue, **458**
  epidermal, 458
  in human blood vessels, 500–501
  in human respiratory system, 510
Epithelium, **458**, 483
EPO. *See* Erythropoietin (EPO)
Equilibrial life histories, **407**, 409
Erectile dysfunction (ED), 568–69
Ergot poisoning, fungal, 330–31
Erosion, chemical cycling and, 440
Erythrocytes, **503**. *See also* Red blood cells
Erythromycin, 55
Erythropoietin (EPO)
  athletic abuse of, 503–4
  genetic engineering of, 221
  high-altitude athletic training and production of, 504
  as protein hormone, 537
Escherichia coli. *See E. coli* bacteria
Esophagus, **480**
Essential amino acids, human, **486**
Essential elements, plant, **626**–27
Essential fatty acids, human, **488**
Essential nutrients, human, **486**–88
  essential amino acids, 486
  essential fatty acids, 488
  food labels and, 488
  minerals, 488
  vitamins, 487
Estrogen, **546**
  after childbirth, 568
  birth control pills of synthetic, 560
  gonad production of, 546
  in human female reproductive cycle, 558–59
  osteoporosis and, 595
  production of, by follicles, 555
  as steroid, 45
  Turner syndrome treatment with, 140
Estuaries, **383**
Ethanol, 93, 106–7
Ethical issues
  on DNA technology, 236–37
  on extinction of species, 327
  on reproductive cloning, 209
  on in vitro fertilization, 570
Ethiopia, origin of *Homo sapiens* in, 366
Ethyl alcohol, 101, 103
Ethylene, **634**
Eudicots, **606**
Eukarya domain, 9, 288–89, **302**. *See also* Eukaryotes
Eukaryotes, **294**. *See also* Animals; Fungi; Plants; Protists
  cells of (*see* Eukaryotic cells)
  Eukarya domain of, 9, 288–89, 302
  in history of life on Earth, 294–95
  sequencing of whole genomes of, 8, 230–33 (*see also* Genomes; Genomics)
Eukaryotic cells, **7**, **58**. *See also* Cells
  animal and plant, 9, 59
  cell cycle of (*see* Cell cycle, eukaryotic)
  energy conversion by chloroplasts and mitochondria in, 68
  gene regulation in, 202–4
  prokaryotic cells vs., 7–8, 58 (*see also* Prokaryotic cells)
European butterflies, effects of global climate change on, 396
European grass snakes, 358*f*
European kestrels, ultraviolet vision of, 599*f*
Eustachian tube, **592**–93
Eutherians, **360**
Evaporation
  in global water cycle, 391
  plant water transport by, 629–30
Evaporative cooling, water and, **30**
Evo-devo (evolutionary developmental biology), **279**

Evolution, 242–44, **245**–67
advantages of asexual and sexual reproduction for, 140, 552–53
amino acid genetic code as evidence for, 180
of antibiotic-resistant bacteria, 18, 71
of bdelloid rotifers without sexual reproduction, 137
of biodiversity (*see* Biodiversity)
of biological novelty (*see* Macroevolution)
of biophilia, 448–49
of bread wheat, 276
of cancer cells in tumors, 215
of chloroplasts and mitochondria, 68
convergent (*see* Convergent evolution)
Charles Darwin's theory on, by natural selection, 10–13, 244–47, 252–54 (*see also* Natural selection)
directed, in engineering of enzymes, 81
DNA profiling in researching, 227, 237
of dogs, 167
of emerging viruses, 194
evidence for, 248–51
evolutionary adaptations and (*see* Evolutionary adaptations)
evolutionary trees representing, 255
form-function correlation and, 457
gene flow as mechanism of, 262
genetic drift as mechanism of, 260–62
global climate change as agent of, 399
of glycolysis for cellular respiration and fermentation, 103
grandmother hypothesis on, of human menopause, 570
of HIV strains, 530
of human fat and sugar cravings, 491
of human lactose intolerance, 51
of humans (*see* Human evolution)
of interdependence of organisms, 637
of lizard horn length as response to predation, 254
major episodes in history of life and, 294–95
mass extinctions and, 269
mechanisms of, 260–65
of membranes, 87
microevolution as modern synthesis of population genetics and evolutionary biology, 256–59
of multicellular life from unicellular colonial protists, 311
of new senses, 598
organization of this book about, 17–18
origin of life in chemical, 296–98
phylogenetic trees and evolutionary relationships in systematics, 286–88
of plant-fungus symbiosis, 332
of plants, 318–19
populations as units of, 256–57
of pre-cells to cells, 298
of primates, 361–62
as property of life, 4–5*f*
in resistance to efforts to eradicate malaria, 242–43
of sickle-cell disease in response to malaria, 265
of steroid hormones and male agression, 547
of symbiotic relationships for pollination and dispersal of angiosperms, 621
of ultraviolet vision, 599
as unifying theme of biology, 10–13
water and, of extraterrestrial life, 33
Evolutionary adaptations, **244**
adaptive coloration as, in response to predation, 430
for animal thermoregulation, 471
to desert biomes, 387
evolution by natural selection and, 11–13, 244–45, 262–64, 378–79 (*see also* Evolution; Natural selection)
flight as, for birds, 359
global climate change as agent of, 399
homologies and, 287
human evolution and ongoing, 367
of humans to different environments, 366
of humans to high-altitude environments, 513
Jean-Baptiste de Lamarck's theory on, 245
of organisms to environmental variability, 378–79
of plants to hot, dry climates, 115–16
of plants to terrestrial biomes, 316–17, 322–23
Evolutionary biology, 378. *See also* Ecology; Modern synthesis
Evolutionary developmental (evo-devo) biology, **279**
Evolutionary trees, 167, **255**. *See also* Phylogenetic trees
Excited state, electron, 112
Excretion, urinary system, **470**
Exercise
cancer prevention or survival and, 129
cardiovascular disease and, 506
effects of, on brain size, 31–32
food calories burned by, 485*t*
for osteoporosis, 595
Exhalation, 511
Exocytosis, **86**
Exons, **182**, 204
Exoskeletons, **347**
Exotoxins, **303**–4
Experimental groups, 16
Experimental models. *See* Model organisms
Experiments, scientific, 15–16. *See also* Case studies; Science
Exponential population growth model, **408**, 409
Expulsion stage, labor, 568
External fertilization, 553. *See also* Fertilization
External innate defenses, 518
Extinctions
effects of global climate change on, 399
human impacts on rate of, 366
humans as invasive species and, 421
loss of biodiversity through, 425
loss of plant diversity through, 327
loss of species diversity through, 426
mass (*see* Mass extinctions)
species endangered and threatened by, 412 (*see also* Endangered species)
Extracellular matrix, **61**, 83*f*, **458**
Extrahuman senses, 574–75, 588, 592, 598–99
Extraterrestrial life, search for, 33
Extremophiles, 302–3
Eyeglasses, 591
Eyes, 589–90. *See also* Vision
Eyespots, mimicry of, 431

F

F_1 generation, **147**
F_2 generation, **147**
Facilitated diffusion, tranport proteins and, **84**
$FADH_2$, 98–99
Fair Trade Certified coffee, 605
Fairy rings, fungal, 328*f*
Fallopian tubes, 555
Familial cancers, 213
Families (taxonomy), **286**
Family pedigrees (family trees), 153–54
Farming. *See* Agriculture
Farsightedness, **591**
Fast-twitch muscle fibers, 91
Fat layers, thermoregulation and, 471
Fats, **43**–44
in adipose tissue, 459
cellular respiration of, 100*f*
chemical digestion of, 477
evolution of human craving for, 491
hydrocarbons in, 38–39*f*
as lipids, 43–44
trans fats, 15–16
Fat-soluble vitamins, 487*t*
Fatty acids
human essential, 488
as lipids, 43–44
Feathers, bird, 359, 379, 471
Feces, **484**
Federal Burea of Investigation (FBI) database, 228
Feedback regulation. *See also* Homeostatic regulation; Regulation
calcium homeostasis, 542
enzyme inhibitors and, 82
glucose homeostasis, 543
during labor and childbirth, 568
Feeding. *See* Food; Nutritional modes; Trophic structures
Feet, embryonic development of, 564
Females
hermaphrodites and, 553
sexual dimorphism and, 264
Females, human
abnormal numbers of sex chromosomes in, 140
depressive illness in, 586
grandmother hypothesis on evolution of menopause in, 570
infertility of, 568–69
osteoporosis in, 595
population momentum and, 418
preganancy of, 564–67
reproductive anatomy of, 555
sex chromosomes of, 165
sex hormones of, 546
Fermentation, **101**–3. *See also* Cellular respiration
as anaerobic process, 101
bioethanol from, 107
evolution of glycolysis for cellular respiration and, 103
in human muscle cells, 101–2
in microorganisms, 102–3
muscle fatigue as lactic acid accumulation from, 102
Ferns, **319**, 321

Fertility
  population momentum and rates of, 418–19
  reduced hybrid, 273
  technologies of (*see* Reproductive technologies)
Fertilization, **131**, **562**, **617**
  after nondisjunction errors, 138
  angiosperm, 617–19
  chromosomal basis of inheritance and, 162–64
  double, in angiosperms, 325
  gametic isolation and, 273
  genetic variation from random, 136
  human, 562, 564
  Gregor Mendel's experiments with, 146–52 (*see also* Mendelian inheritance)
  plant, 317, 617
  in sexual reproduction, 122, 131, 617
  types of, 553
  in vitro fertilization, 550–51, 569–70
Fertilizers, plant, 441–43, **627**
Fetal development, human, 565–68. *See also* Human embryonic development
Fetal genetic screening, 157
Fetus, **555**
Fever, **467**, 520
Feynman, Richard, 293
Fiber, dietary, 42
Fibers
  cytoskeleton, 69
  muscle, 460
  protein, 458–59
Fibrin, **505**
Fibrinogen, **505**
Fibrous connective tissue, **459**, 595
Fibrous root systems, 607
Fight-or-flight responses
  adrenal gland hormones and, 544–45
  autonomic nervous system and, 582
  in cell signaling, 87
  human heart pacemaker and, 500
Filtrate, urinary system, **469**–70
Filtration, urinary system, **470**
Finches, Galápagos Islands
  age structure of, 405
  biodiversity of, 270
  evolution of, 12–13
  founder effect of, 262
Fire
  in chaparral biomes, 388
  cheatgrass and, 414
  as effect of global climate change, 397
  in savanna biomes, 387
  secondary ecological succession after, 437
  in temperate grassland biomes, 388
First trimester, pregnancy, 566
Fishes
  androgens and male aggression in, 547
  characteristics of, 356
  emergence of new senses in, 598
  extinctions of species of, 426
  gills of, 507–8*f*
  overharvesting of, 413, 428
  unsaturated fatty acids in fats of, 44
Fission, **552**, 553
Fitness, relative, 262–63
FitzRoy, Robert, 246
Five-carbon sugars, nucleic acids and, 49
Five-kingdom system (taxonomy), 288–89
Fixed species idea, 245
Flaccid plant cells, 85
Flagella, 58, **70**
Flagellates, **308**
Flat-tailed horn lizard case study, 254
Flatworms (Platyhelminthes), **344**
Flesh-eating disease, 61, 303
Fleshy fruits, 620
Flexible-fuel vehicles, 107
Flight
  bird, 359
  insect, 350
  mammalian, 360
  vertebrate, 350
Flooding
  dams and, 381
  global climate change and, 373
  secondary ecological succession after, 437
Flour beetles, population growth of, 410
Flowering plants. *See* Angiosperms
Flowers, **319**, **617**
  in angiosperm life cycle, 325–26
  eudicot vs. monocot, 606
  evolution of, in angiosperms, 319
  photoperiod and blooming of, 636–37*f*
  structure of, 324, 617
Flowing water biomes, 381
Fluid mosaics, plasma membranes as, **60**
Fluorescent light, 112
Fluoride, dental health and, 24
Fluorine (F), 24
Fluoxetine, 586
Flu viruses. *See* Influenza viruses
Follicles, **555**–57
Follicle-stimulating hormone (FSH), 540, 557–59
Food. *See also* Diets; Digestive systems
  angiosperms as human, 326, 605–6
  animal nutrition and, 476–78
  annuals as human, 613
  breeding of crops for, by humans, 145
  Calories of, and human activities, 78
  carbon footprints and, 398
  cellular respiration as aerobic harvest of energy from, 94 (*see also* Cellular respiration)
  dietary fats (*see* Dietary fats)
  digestion of, by lysosome enzymes, 66
  ecosystem modes of nutrition and, 6, 92 (*see also* Nutritional modes)
  environmental costs of human, 439
  fermentation as anaerobic harvest of energy from, 101–3
  fungi as human, 331–32
  genetically modified (GM), 221–22, 235–36
  for global human population, 419–20
  human processing of (*see* Digestive system, human)
  kingdoms of Eukarya domain and, 9
  nutritional modes of eukaryotes and, 289
  nutritional requirements for human, 485–88 (*see also* Nutrition, human)
  seaweeds as, 310–11*f*
  sympatric speciation and crops for, 276
  trophic structures, food chains, and (*see* Food chains; Trophic structures)
  white truffles, 314–15
Food and Drug Administration (FDA), 236, 488, 560
Food chains, **432**
  energy flow in, 438–39
  human, 439
  in trophic structure food webs, 434
  in trophic structures, 432–33
Food-conducting cells, plant, 612, 630–31
Food labels, 485, 488
Food poisoning, 303
Food vacuoles
  lysosomes and, 66
  phagocytosis and, 86, 478
Food webs, **434**
Foot, mollusc, 343
Forams, **308**, 309*f*
Forebrain, 583
Forensics, **226**
  DNA profiling in, 17, 218–19, 226, 228 (*see also* DNA profiling)
  forensic entomologists in, 352
  genomics in, 231–32
Foreskin, 554
Forests. *See also* Deforestation; Trees
  human impacts on, 392
  temperate broadleaf, coniferous, and temperate rain, 389
  tropical, 386 (*see also* Tropical forests)
  wildfires in, as effect of global climate change, 397
Form and function correlation, animal, 456–57
Formulas, molecular and structural, 27*f*
Fossil fuels, **321**
  as abiotic reservoir for carbon, 441
  biofuels and, 107
  from ferns, 321
  greenhouse gases from burning, 395, 441–42
  hydrocarbons in, 38–39*f*
  oil spills and (*see* Oil spills)
  reducing emissions from, 398
Fossil record, **248**
  evidence for evolution in, 248
  evidence for evolution of eukaryotes in, 306
  evidence for speciation in, 270
  evidence for speciation patterns in, 277
  evidence of mass extinctions in, 269
  geologic time scale of, 280–82
  of mammalian diversification after dinosaur mass extinction, 289
Fossils, **245**
  animal, 339
  fish, 356
  fixed species idea and, 245
  of fungi, 328
  history of life and, 10
  hominin, 364–65
  insect, 351
  methods of dating, 270, 282
  plant, 318
  of prokaryotes and eukaryotes, 58
Founder effect, **262**
Four-stage hypothesis on origin of life, 296–98
Fox, Michael J., 231*f*
Fox terriers, 157
Fractures, bone, 595
Fragmentation
  asexual reproduction by, 552
  biodiversity in habitat, 427
  biodiversity in tropical forest, 446
  biome, 386

Franklin, Rosalind, 175*f*, 177
Free ribosomes, 63
Freshwater biomes, 380–81. *See also* Biomes
  animal osmoregulation in, 468–69
  human impacts on, 392–93
  lakes and ponds, 380
  rivers and streams, 381
  wetlands, 381
Frogs, 357, 553
Frontal lobes, cerebral cortex, 584–85
Fructose, 40
Fruit flies (*Drosophila melanogaster)*
  genome of, 230
  homeotic genes of, 279
  study of linked genes and crossing over in, 163–64
Fruits, **326**, **620**
  angiosperm, 326, 620
  ethylene in ripening of, 634
  gibberellins in formation of, 635
  ovaries as, 618
FSH (follicle-stimulating hormone), 540, 557–59
Fuels. *See* Fossil fuels
Fukushima nuclear disaster, 26, 624–25
Functional groups, 38–**39**
Function and form correlation, animal, 456–57. *See also* Animal structure and function
Fungi, **328**–35
  as biological control of kudzu, 415
  cells of (*see* Eukaryotic cells)
  commercial uses of, 331–32
  as decomposers, 330, 433
  diversity and importance of, 328
  ecological impact of, 330–32
  ergot poisoning from, as cause of Salem witch hunt, 331
  Eukarya domain and Fungi kingdom of, 9, 289
  nutritional mode, structure, and reproduction of, 329
  parasitic, 330, 426
  as pathogens, 432
  sexually transmitted diseases from, 560–61*t*
  symbiosis of plants and, 314–16, 328, 332, 430, 628, 637
  truffles, 314–15
Fungi kingdom, 9, 289
Fur
  as anatomical response to environment, 379
  as thermoregulation response, 471
Fur seals, population growth of, 409

G

Gage, Phineas, 585
Galápagos Islands
  Charles Darwin's study of biodiversity of, 11, 246–47, 270
  finches of (*see* Finches, Galápagos Islands)
  overexploitation in, 428
Galápagos tortoise, 270*f*, 428
Gallbladder, 479, **482**
Gallo, Robert, 523
Gallstones, 482
Gametangia, **317**
Gametes, **122**, 131, **553**
Gametic isolation, 273
Gametogenesis, **556**
  oogenesis, 556–57
  spermatogenesis, 556
Gametophytes, **320**, **618**
  angiosperm, 325, 618–19
  bryophyte, 320
  gymnosperm, 322–23
Gannets, population growth of, 410*f*
Garden peas, Gregor Mendel's study of, 146–51. *See also* Mendelian inheritance
Garlic, asexual reproduction of, 617*f*
Garrod, Archibald, 178
Gas exchange systems. *See* Respiratory systems
Gas state of matter, 24
Gastric bypass surgery, 481
Gastric juice, **480**–81
Gastric ulcers, 481
Gastroesophageal reflux disease (GERD), 481
Gastropods, **343**
Gastrovascular cavity, **342**, **478**
Gastrula, **338**, **563**
Gastrulation, **563**
Gaurs, 208–9*f*
Gause, G. F., 429
Gefitinib drug, 233
Gel electrophoresis, **228**–29, 310
Gene cloning, **222**–24
Gene expression, 178–87, **200**
  determination of phenotypes from genotypes in, 178, 185, 200
  in human embryonic development, 563–64
  mutations during, 186–87
  patterns of, in differentiated cells, 200
  processing of eukaryotic RNA in, 182
  regulation of (*see* Gene regulation)
  stages of, 178–79, 185, 202
  transcription stage of, 181, 185
  translation stage of, 182–85
  triplet genetic code for amino acids in, 179–80
  in viable IVF embryos, 569
  visualizing, with DNA microarrays, 206–7
Gene flow, **262**, 274
Genentech company, 220–21
Gene pools, **256**
  analyzing, 258–59
  mechanisms of microevolution of, 260–62
  microevolution as changes in, 259
  in study of evolution of populations, 256–57
Gene regulation, 198–99, **200**–217
  in bacteria, 200–201
  cell signaling in, 205
  of cellular differentiation and gene expression, 200–207 (*see also* Gene expression)
  of cloning of plants and animals, 207–10
  DNA microarrays in study of, 206–7
  of DNA packing, 202–3*f*
  in effects of smoking on development of lung cancer, 199
  in eukaryotic cells, 202–4
  and evolution of cancer cells, 215
  and genetic basis of cancer, 198–99, 211–15
  homeotic genes in, 205–6
  of initiation of transcription, 203
  of initiation of translation, 204
  microRNAs in, 204
  in mutations involved in childhood cancer tumors, 212
  of protein activation and breakdown, 204
  of RNA processing and breakdown, 204
Genes, **7**, **49**
  alleles of (*see* Alleles)
  cancer and, 211
  cloning of, 222–24
  disease-associated, in human genome, 231
  diversity of, in biodiversity, 426
  DNA as chemical material of, 7–8, 49–50 (*see also* DNA (deoxyribonucleic acid))
  in emergence of new senses, 598
  in eukaryotic chromosomes, 123–25
  genomes and, 8 (*see also* Genomes)
  high-altitude mutations of, 513
  homeotic, 205–6, 279
  linked, 163
  locus (loci) of, 149
  mapping, with linkage maps, 164
  in molecular systematics, 287
  origin of, in origin of life, 298
  protein synthesis by, 48–50 (*see also* Gene expression)
  regulation of expression of (*see* Gene regulation)
  selecting, from genomic libraries, 225
  sex-linked, 165–66
  synthesis of, for recombinant DNA technology, 225
  in weight gain, 490–91
Genetically modified (GM) organisms, **221**
  as foods, 221–22, 235–36
  with resistance to viral infection, 190
Genetic code, 179–**80**, 182–83
Genetic diversity. *See also* Genetic variation
  in biodiversity, 426
  reproductive cloning and, 209
Genetic drift, **260**–62
  bottleneck effect in, 260–61
  founder effect in, 262
Genetic engineering, **220**. *See also* DNA technology; Nanotechnology
  biotechnology and, 220
  of enzymes, 81
  of insulin, 8
  of organisms (*see* Genetically modified (GM) organisms)
  of plants to resist viral infection, 190
  to produce foods, 221–22, 235–36
  to produce medicines, 220–21
  to produce pharmaceutical (pharm) animals, 222
  recombinant DNA technology in, 220 (*see also* Recombinant DNA technology)
  science, technology, and, 17
Genetic Information Nondiscrimination Act of 2008, 237
Genetic recombination, **137**, 163–64
Genetics, **146**. *See also* DNA (deoxyribonucleic acid); Genes; Genomes; RNA (ribonucleic acid)
  of angiosperm life cycle, 618
  case study on emergence of new senses and, 598
  case study on genetic basis of coat variation in dogs, 157
  case study on genetic basis of lactose intolerance, 51
  DNA technology (*see* DNA technology)
  dog breeding as longest-running genetic experiment, 144–45

Genetics (*Continued*)
evidence for speciation in, 270
genetic advantages of sexual reproduction, 553
genetic basis of cancer, 198–99, 211–15 (*see also* Cancer)
genetic disadvantages of asexual reproduction, 552
human genetic disorders, 154–57
molecular biology and, 174
population, in health science, 259
as study of heredity and inheritance, 146 (*see also* Inheritance)
synthesis of evolutionary biology and (*see* Modern synthesis)
Genetic testing
for human genetic disorders, 157
kits, 236–37
prenatal, 565
in vitro fertilization and, 570
Genetic variation, 135–37. *See also* Genetic diversity
crossing over and, 136–37
independent assortment of chromosomes and, 135–36
prokaryotic reproduction and, 301
random fertilization and, 136
from sexual reproduction, 553
sources of, 257–58
Genital herpes virus, 191, **561**
Genghis Khan, 237
Genomes. *See also* Genes
Neanderthal, 233, 365
sequenced, 230*t*
sequencing of, 8, 230–33 (*see also* Genomics)
synthesis of artificial, by synthetic biology, 293
using genomic libraries of, 224–25
whole, of dogs, 157, 167
Genomic libraries, **224**–25
Genomics, **230**–33
bioinformatics in, 232
in forensics, 231–32
genome-mapping techniques, 232–33
Human Genome Project, 230–31
screening lung cancer patients using, 233
sequencing of whole genomes of organisms for, 8, 230–33 (*see also* Genomes)
Genotypes, **149**
analyzing gene pools of, 258–59
determination of unknown, by testcrosses, 152
family pedigrees and, 153–54
gene expression as determination of phenotypes from, 178
genetic variation and, 257
phenotypes vs., 149, 178
Genus names, **285**–86
Geographic distribution of species
evidence of evolution in, 249
plate tectonics and, 283
Geographic isolation
allopatric speciation and, 274–75
evolution by natural selection and, 11
evolution of populations and, 256
founder effect of, 262
Geologic processes, chemical cycling and, 440–41
Geologic time scale, fossil record and, **280**–82
Germination, seed, **323**, **618**–20, 635
Gestation, **564**. *See also* Pregnancy
Gestational diabetes, 544. *See also* Diabetes mellitus (diabetes)
Ghrelin, 538
Giant bacteria, 300*f*
Giant tortoises, 270*f*
Giant tube worms, 376*f*
Giardia, 308*f*
Gibberellins, **635**
Gibbons, 251*f*, 361*f*–62*f*
Gigantism, 541
Gila monster, 358*f*
Gills, 356, **507**–8*f*
Gilpin, Max, 455
Glands
autonomic nervous system and, 582
endocrine system, 538–39*t* (*see also* Endocrine systems)
Glans
female, 555
male, 554
Glaucoma, 589
Global biogeochemical cycles, 440
Global climate change, 394–99
accumulation of greenhouse gases and, 395
as agent of evolution by natural selection, 399
carbon cycle, carbon dioxide, and, 441
cheatgrass and, 414
effects of, on ecosystems, 397
effects of, on freshwater biomes, 393
effects of, on global water cycle, 391
effects of, on polar bears and penguins, 372–73
effects of, on species distribution, 396
effects of, on terrestrial biomes, 386
fossil fuels and, 321
global human ecological footprint and, 419
greenhouse effect and, 394
human carbon footprints and, 398
nitrogen cycle and, 442
photosynthesis and, 110
tree ring data on, 615
Global ecological footprints, 420
Global epidemic, H1N1 influenza virus, 173
Global hectares, 419–20
Global warming. *See* Global climate change
Global water cycle, 391, 428
Glucagon, **543**–44
Glucocorticoids, **545**
Glucose
in cellular respiration, 94–97
in chemical cycling between photosynthesis and cellular respiration, 92–93
in fermentation, 101
in glycolysis, 96–97
homeostasis of, 465
linear and ring structure of, 40
pancreas hormones and homeostasis of, 543–44
in photosynthesis, 109
in redox reactions, 95
Gluten, 484
Glyceraldehyde 3-phosphate (G3P), 115
Glycerol molecules, fats and, 43
Glycine, 46
Glycogen, **42**
Glycolysis, **96**
in cellular respiration, 96–98, 100
evolution of, 103
in fermentation, 101–3
nanotechnology and, 75
Goiter, iodine deficiencies and, 24–25*f*, 541
Golden rice 2, 222
Golden toads, extinction of, 426*f*, 444
Golgi, Camillo, 65
Golgi apparatus, **65**
Gonads, **546**, **554**
endocrine system functions of, 539*t*, 546
in human sexual reproduction, 554–55
Gonorrhea, 560–61*t*
Goodall, Jane, 14*f*
Goose bumps, 471
Gorillas, 251*f*, 361*f*–62*f*
Gould, Stephen Jay, 364
Gradual pace pattern, speciation, 277
Grana, **68**, **108**
Grand Canyon, 248*f*, 275*f*
Grandmother hypothesis, menopause and, 570
Grapes, 635
Grasshoppers, 350*f*–51*f*, 352
Graves' disease, 542
Gravitropism, **636**
Gray-headed chickadees, 378*f*
Gray tree frogs, 357*f*
Gray wolves, 208–9*f*
Great Lakes food chain, biological magnification of PCBs in, 433
Great Pacific Garbage Patch, 383
Great tits, population growth of, 410
Greater arid-land katydid, 351*f*
Green algae, **310**–11, 318
Green cones, eye, 590
Green energy. *See* Biofuels
Greenhouse effect, **394**–95. *See also* Global climate change
Greenhouse gases, **394**–95, 398
Green manure, 629
Ground state, electron, 112
Ground tissue system, **610**–11
Groups, experimental vs. control, 16
Growth
cell division and, 122
determinate vs. indeterminate, 613
plant (*see* Plant growth)
population (*see* Population growth)
as property of life, 4
Growth factors, **211**
Guanine (G), 7, 49–50, 174–**75**
Guard cells, **611**, 630
Gulf of Mexico
dead zone in, 443
oil spill in, 425
Gulls, biological magnification of PCBs in, 433
Gymnosperms, **319**, 322–23

H

H1N1 influenza virus, 172–73, 194
Habitat isolation, 272
Habitats, **375**
declining biodiversity in destruction of, 427
in ecology, 375
limiting factors of, for population growth, 409
movement of life from aquatic to terrestrial, 295
protist, 307–8
red-cockaded woodpecker, 412
Haemophilus influenzae, 230, 303*f*
Hagfishes, 354, 356*f*
Hair
as mammalian adaptation, 360
thermoregulation and, 471
Hair cells, ear, 592–93
Halophiles, 302–3
Hammer, ear, 592–93
Hands, embryonic development of, 564
Haploid cells, **131**

Hardy-Weinberg equilibrium, **259**, 262
HCG (human chorionic gonadotropin), 522, 559
Head, insect, 350*f*
Health, human. *See* Diseases and disorders, human
Health science, population genetics in, 259. *See also* Medicine
Hearing, 592–93
Heart attacks, 500–501, 505–6. *See also* Cardiovascular disease
Heartburn, 481
Heart disease. *See* Cardiovascular disease
Heart murmurs, **499**
Heart muscle, 460
Heart rate, **499**–500
Hearts, **499**. *See also* Cardiovascular systems
  animal, 496–97
  human, 499–500 (*see also* Cardiovascular disease; Heart attacks)
Heartwood, tree, 616
Heat, **30**, **77**
  cellular respiration and body, 77–78 (*see also* Body heat)
  energy conversions and generation of, 77
  as energy loss in ecosystem energy flow, 437
  greenhouse effect and, 394
  sensory receptors of, 588
  solar energy and uneven, in zones of Earth, 384
  temperature vs., 30
Heat illness, 455
Height, polygenic inheritance of human, 160–61
Heimlich maneuver, 510
Helicobacter pylori, 481
Helium (He), 25
Helper T cells, **526**
  in AIDS, 530
  in cell-mediated immune response, 526–27
Heme chemical group, 204, 512
Hemings, Sally, 226
Hemispherectomy, 585
Hemoglobin, **503**. *See also* Blood
  gene regulation of synthesis of, 204
  human respiratory system and role of, in gas transport, 503, 512
  sickle-cell, as evolutionary response to malaria, 47, 160, 265, 366
  transgenic pigs and human, 222
Hemophilia, **166**, 505
Hemorrhagic fevers, human-caused disturbances and, 436
Hepatitis virus, 190, 221, 525
Herbicides, synthetic, 416, 634
Herbivores, **432**–33, **476**
Herbivory, **431**, 605
Herceptin, 522
Heredity, **146**. *See also* Inheritance
  genetics as study of, 146 (*see also* Genetics)
  molecular biology as study of, 174
Hermaphrodites, **553**
Heroin, 580
Herpesviruses, 190–91
Herring gulls, in biological magnification of PCBs, 433
Heterotrophs, **92**, 302, 307, 432–3
Heterozygous organisms, **148**–49
HGH. *See* Human growth hormone
Hibernation, 389, 471
Hiccups, 511
Hierarchical classification of species, 285–86. *See also* Systematics; Taxonomy
Hierarchical organization of animal bodies, 456. *See also* Animal structure and function
High-altitude adaptations, human, 366, 513
High-altitude athletic training, 495, 504
High blood pressure, 501
High-fructose corn syrup, 41
Hill, A. V., 102
Hindbrain, 583
Hinge joints, **594**
Hirudo medicinalis, 345*f*–46
Histamine, **520**, 528
Histones, **124**
HIV (human immunodeficiency virus), **192**
  as emerging virus, 194
  evolution of drug-resistant strains of, 253
  human-caused disturbances and, 436
  as retrovirus causing AIDS, 192–93, 523 (*see also* AIDS (acquired immunodeficiency syndrome))
  as RNA virus, 190
  search for vaccine against, 516–17
  as sexually transmitted disease, 561
Hobbit people, 336–37, 365
Hodgkin's disease, 529
Holly trees, asexual reproduction of, 617*f*
Homeostasis, **465**–66. *See also* Homeostatic regulation
Homeostatic centers, brain, 582
Homeostatic regulation, 465–71
  by cardiovascular systems, 506
  by endocrine systems, 538–39*t*
  homeostasis in, 465–66
  negative and positive feedback in, 466
  osmoregulation in, 468–69
  thermoregulation in, 467–68, 471
  by urinary systems, 469–70
Homeotic genes, **205**
  in gene regulation, 205–6
  in macroevolution by developmental processes, 279
Home pregnancy tests, 522, 559
Home run records, steroid abuse and, 534–35
Hominins, **363**. *See also* Human evolution
Homo erectus, 364–65
Homo floresiensis, 336*f*–37, 365
Homo habilis, 364–65
Homologies, **250**
  analogies vs., in phylogenetic trees, 286–87
  as evidence of evolution, 250
  in evolutionary trees, 255
Homologous chromosomes, **130**
  genetic variation from crossing over between, 136–37
  independent assortment of, 135–36
  Gregor Mendel's law of segregation and, 149
  in sexual reproduction, 130–31
Homo sapiens. *See also* Human evolution; Humans
  interbreeding of *Homo neanderthalensis* and, 365
  meaning of scientific name of, 285
  origin and dispersal of, 366
Homozygous organisms, **148**–49
Hooke, Robert, 56
Hookworms, 346*f*
Hormone replacement therapy, 595
Hormones, animal, **536**
  antagonistic, 542
  in cell signaling, 87
  endocrine systems and, 536–37
  in gene regulation, 205
  in human female reproductive cycle, 558–59, 595
  in human labor, 568
  in human urinary system function, 470
  steroid, 45, 535 (*see also* Steroid hormones)
Hormones, plant, **632**–35
  abscisic acid, 635
  auxins, 632–34
  cytokinins, 634
  ethylene, 634
  gibberellins, 635
  phototropism and, 633
  synthetic, 634
  types of, 632*t*
Horned lizard case study, 254
Hosts, parasite, **432**
Hot spots, biodiversity, 444
HPV (human papillomavirus), 561
Human chorionic gonadotropin (HCG), 522, 559
Human embryonic development, 562–68
  childbirth in, 568
  concepts of, 563–64
  fertilization in, 562
  pregnancy and early, 564–65
  stages of pregnancy in, 566–67
Human evolution. *See also* Humans
  Australopithecus and bipedalism in, 364
  common misconceptions about, 363
  Homo erectus and global dispersal in, 364
  Homo floresiensis and hobbit people in, 336–37, 365
  Homo habilis and inventive minds in, 364
  Homo neanderthalensis in, 365
  human adaptations and ongoing, 367
  origin and dispersal of *Homo sapiens* in, 366
  primate evolution and, 361–62
  timeline of, 363*f*
Human gene therapy, **234**
Human Genome Project, **230**–33
Human growth hormone (HGH), **541**
  ethical issues on, 236
  genetic engineering of, 221
  as pituitary secretion, 541
Human papillomavirus (HPV), 561
Human population
  age structures of, 418–19
  ecological footprints of, 419–20
  ecosystem energy flow and trophic structure of, 439
  evolution of, as invasive species, 421
  history of growth of, 417
  population ecology and, 404
Human reproduction, 550–73
  concepts of animal reproduction and, 552–53
  contraception and, 559–60
  embryonic development and, 562–68 (*see also* Human embryonic development)
  female reproductive anatomy in, 555
  female reproductive cycle in, 558–59
  gametogenesis in, 556–57
  gonads and sex hormones in, 546
  grandmother hypothesis on evolution of menopause in, 570
  male reproductive anatomy in, 554

Human reproduction (*Continued*)
reproductive technologies and, 550–51, 568–70
sexually transmitted diseases and, 560–61
using DNA profiling to identify viable IVF embryos in, 569
Humans. *See also* Animals
ABO blood groups of, as example of codominant alleles, 159
athletes (*see* Athletes)
behavioral responses of, to environmental variability, 379
body thermoregulation of, 454–55
breeding of plants and animals by, 144–45, 151, 156, 167
carbon footprints of, 398
cell signaling in, 87
cellular respiration in muscle cells of, 90–91
cellular structures of skin cells of, 74
chemical composition of bodies of, 24
cilia and flagella of cells of, 70
culture of, 366
dependence of, on water, 22–23
digestive system of (*see* Digestive system, human)
diseases of (*see* Diseases and disorders, human)
in disturbances of communities, 436
DNA profiling of male ancestry of, 237
DNA profiling of mummified and ancient, 227
effects of global climate change on, 397–98
embryos of, 251*f*
emergence of, in history of life, 295
epithelial tissue in linings of organs of, 458*f*
evaporative cooling by sweating, 30
evolution of (*see* Human evolution)
evolution of biophilia in, 448–49
family pedigrees of, 153–54
fermentation in muscle cells of, 101–2
food calories and activities of, 78 (*see also* Food)
gene flow from migration of, 262
height of, as example of polygenic inheritance, 160–61
homeostatic regulation in (*see* Homeostatic regulation)
homologous and sex chromosomes of, 130*f*–31
hormones of, 536–37 (*see also* Endocrine systems; Hormones, animal)
immune system of (*see* Immune systems)
impacts of, on accumulation of greenhouse gases, 395
impacts of, on biomes, 392–93
impacts of, on freshwater biomes, 380–81
impacts of, on global water cycle, 391
impacts of, on loss of biodiversity, 425
impacts of, on marine biomes, 383
impacts of, on nitrogen cycle, 442
impacts of, on population growth of organisms, 408
impacts of, on species extinctions, 269, 426
importance of fungi for, 328, 331–32
importance of insects for, 352
importance of prokaryotes to, 299
incomplete dominance in, 158
interdependence of organisms and, 637
as invasive species, 421
life cycle of, 131
magnetic resonance imaging (MRI) of brains of, 31–32
as mammals and primates, 361
meaning of *Homo sapiens* scientific name for, 285 (*see also Homo sapiens*)
nanotechnology and sperm cells of, 75
nervous system of (*see* Nervous systems)
number of chromosomes in cells of, 123*f*, 130
nutrient pollution by, 443
nutrition for (*see* Nutrition, human)
paedomorphosis of skulls of, 279
patterns of gene expression in differentiated cells of, 200
population of (*see* Human population)
reproduction of (*see* Human reproduction)
reproductive cloning of, 209
sequencing of whole genome of, 230–33 (*see also* Genomics)
structural hierarchy of bodies of, 456*f*
structure and function of bodies of (*see* Animal structure and function)
survivorship curves for, 406
symbiotic bacteria and, 332
technology and environmental impacts of, 18
viruses that infect, 188*f*–89, 190–94
Humoral immune response, **526**–27
Humulin, genetic engineering of, 220–21
Huntington's disease, **156**
Hurricane Katrina, phytoremediation after, 625
Hybrids, **147**
cross-fertilization and, 147
postzygotic reproductive barriers and, 273
sympatric speciation and polyploid, 276
Hydras, 342, 464, 478, 552
Hydration. *See* Dehydration
Hydrocarbons, **38**–39. *See also* Fossil fuels
Hydrochloric acid, gastric juice as, 480–81
Hydrogen (H). *See also* Hydrogen gas (H_2)
in amino acids, 46
in composition of human bodies, 24
electron arrangement of electrons of, 26
pH and and ions of, 32
Hydrogenation, 15–16, **44**
Hydrogen bonds, **28**, 50
Hydrogen gas (H_2). *See also* Hydrogen (H)
alternative representations of, 27*f*
in photosynthesis, 109
in redox reactions, 95
Hydrolysis, **39**, 477
Hydrophilic molecules, **42**
amino acid side groups as, 46*f*
carbohydrates as, 42
hydrophobic molecules vs., 43
in plasma membranes, 60
Hydrophobic molecules, **43**
amino acid side groups as, 46*f*
hydrophilic molecules vs., 43
lipids as, 43
in plasma membranes, 60
Hydrothermal vents, deep-sea, 297, 299*f*, 376*f*, 382–83
Hydroxide ions, pH and, 32
Hymen, **555**
Hypercholesterolemia, **158**
Hyperopia, 591
Hypertension, **501**
Hyperthyroidism, 541–42
Hypertonic solutions, **84**–85
Hyperventilating, 511
Hyphae, **329**
Hyponatremia (water intoxication), animal, 85
Hypothalamus, **540**, **583**
endocrine system functions of, 539*t*, 540–41, 583
in human female reproductive cycle, 558
stress responses of, 545
thermoreceptors and, 588
Hypotheses, science and, **14**–17, 244. *See also* Case studies
Hypothesis-driven science, **14**–16, 374. *See also* Science
Hypothyroidism, 541–42
Hypotonic solutions, 84–**85**

I

Ibuprofen, 520, 588
Ice, biological significance of floating of, 30–31
Ichthyosaur fossils, 245
Identical twins
development of, 563
environmental influences and, 161
Immune disorders, 528–30
AIDS, 530
allergies, 528
autoimmune diseases, 529, 595
HIV evolution as, 530
immunodeficiency diseases, 529
multiple sclerosis, 577
Immune systems, 516–17, **518**–33
adaptive defenses of, 521–27
antibiotic-resistant bacteria and, 61
appendix in, 484
cancer cells and, 129
disorders of, 528–30, 577
fever in, 467
HIV/AIDS and, 192–93, 516–17, 523, 530
innate defenses of, 518–21
vertebrate, 463*f*
viruses and, 191
Immunization, 525
Immunodeficiency diseases, **529**. *See also* AIDS (acquired immunodeficiency syndrome); HIV (human immunodeficiency virus)
Immunological memory, 525
Impotence, **568**–69
Inbreeding, **155**–56
Incomplete dominance, **158**
Incus, ear, 592–93
Independent assortment of chromosomes, 135–36, 258
Indeterminate growth, plant, **613**. *See also* Plant growth
Indigestion, 501
Individual variation, 11, 252–53

Induced fit, enzyme, **82**
Induction, **563**–64
Industrial waste pollution, 393
Infant mortality, high-altitude adaptations and, 513
Infection, immune system response to. *See* Immune systems
Inferior vena cava vein, 498, 502
Infertility, 550–51, **568**–69
Inflammatory response, **520**
  in allergies, 528
  as internal innate defense, 520
  in large intestine, 484
Influenza viruses, 172–73, 190
Infrasound sense, elephant, 575
Ingestion, **476**
  animal, 289, 338*f*, 476
  human, 484*f*
  protist, 308*f*
  seed dispersal by, 326*f*
Ingroups, cladistics and, 287–88
Inhalation, 511
Inhalation anthrax, 231, 304
Inheritance. *See also* Heredity
  of cancer, 213
  chromosomal basis of, 162–67 (*see also* Chromosomal basis of inheritance)
  DNA as basis of, 174 (*see also* DNA (deoxyribonucleic acid))
  dog breeding and, 144–45, 157, 167
  evolution by natural selection and, 10–13, 253
  family pedigrees and, 153–54
  genetic testing and, 157
  of human diseases and disorders, 154–57
  Mendelian (*see* Mendelian inheritance)
  origin of self-replicating biological molecules and, 298
  polygenic, and genetic variation, 257
  polygenic, of human height, 160–61
  role of environment in, 161
  scientific study of heredity and, 146 (*see also* Genetics; Heredity; Molecular biology)
Inhibiting hormones, 540
Initiation phase, transcription, 181, 203
Initiation phase, translation, 184, 204
Injuries, skeletal, 595
Innate defenses, **518**–21
  adaptive defenses vs., 518 (*see also* Adaptive defenses)
  external, 518
  internal, 519–20
  lymphatic system and, 520–21
Inner ear, **592**–93
Innocence Project, DNA profiling and, 226
Inorganic fertilizers, 627
Inorganic nutrients. *See* Nutrients, inorganic
Insecticides
  synthetic, 416
  toxins as herbivory defenses and, 431
Insects, **350**–52
  anatomy of, 350
  angiosperm pollination and dispersal by, 352, 619, 621, 637
  diversity of, 351–52
  in savannas, 387
  tracheal systems of, 508
Insulation, thermoregulation and, 471
Insulin, **543**. *See also* Diabetes mellitus (diabetes)
  gene regulation of synthesis of, 204
  genetic engineering of, 8, 220–21
  glucose homeostasis and, 100, 543–44
Insulin-dependent diabetes, 544. *See also* Diabetes mellitus (diabetes)
Integrated pest management, 416
Integration, nervous system, **576**
Integumentary systems, vertebrate, 463*f*
Intercellular joining, membrane proteins and, 83*f*
Interdependence of organisms, 624–25, 633, 637
Interferons, **519**
Intergovernmental Panel on Climate Change (IPCC), 394
Intermediate fibers, cytoskeleton, 69
Internal fertilization, 553. *See also* Fertilization
Internal innate defenses, 519–20
Internal timekeeper, 583
International Union for Conservation of Nature, 427
Interneurons, **576**
Internodes, stem, **608**
Interphase, **125**
  meiosis, 131*f*–32*f*
  mitosis, 125–26*f*
Interspecific competition, **429**
Interspecific interactions, **428**–32
  classification of, 428
  herbivory, 431
  interspecific competition, 429
  mutualism, 430
  parasites and pathogens, 432
  predation, 430–31
Interstitial fluid, **465**
  capillaries and chemical exchange between blood and, 502
  in circulatory systems, 496
  homeostasis and, 465, 506 (*see also* Homeostatic regulation)
Intertidal zone, **383**
Intraspecific competition, **410**, 429
Introns, **182**, 204
Invasive species, **413**
  biological control of, 414
  declining biodiversity and, 427
  humans as, 421
  lionfish as, 402*f*–3
  population ecology and, 413–14
Invertebrates, **341**–53
  annelids, 345–46
  arthropods, 347–52
  chordate, 354
  cnidarians, 342
  echinoderms, 353
  flatworms, 344
  molluscs, 343
  as pathogens, 432
  roundworms, 346
  sponges, 341
In vitro fertilization (IVF), 550–51, **569**–70. *See also* Reproductive technologies
Involuntary muscle, 460
Involuntary nervous system. *See* Autonomic nervous system
Iodine (I)
  thyroid hormones and, 541
  as trace element in human diets, 24–25*f*
Iodized salt, 24
Ion channels
  in emergence of new senses, 598
  in nervous system signal transmission, 577–80
Ionic bonds, **27**
Ionic compounds, 27
Ions, **27**, 32
Iridium, dinosaur mass extinction by meteor impact and, 284–85
Iris, **589**
Iron deficiency, 512
Irrigation, 391
Islet cells, 543
Isolation, 11. *See also* Geographic isolation
Isomers, **40**
Isopods, 349
Isotonic solutions, 84–**85**
Isotopes
  radiometric dating using radioactive, 282
  structure of, **25**–26

J

Jacob, François, 201
Jaguars, taxonomy of, 285*f*
Japanese earthquake and tsunami, 283*f*
Japanese nuclear disaster, 26, 624–25
Jawless fishes, 356
Jefferson, Thomas, 226
Jellies (jellyfish), 342
Jeweled beetle, 351*f*
Jewish ancestry, 237
Joints, skeletal system, 594
Jones, Marion, 45*f*
J-shaped curve, population growth rate, 408–9
Judeo-Christian culture, 245

K

Kale, artificial selection of, 13*f*
Kangaroos, 360*f*
Karyotypes, **130**
Kelp, 108*f*, 310–11*f*, 435
Kestrels, ultraviolet vision of, 599*f*
Keystone species, **435**
Kidneys, 469–70, 540, 544–45
Kilocalories (kcal), food, 78, **485**
Kinetic energy, **76**
Kingdoms (taxonomy), 9, **286**, 288–89
King snakes, mimicry in, 430–31*f*
Kissimmee River Restoration Project, 447
Klamath weed, biological control of, 414
Klinefelter syndrome, 140
Koalas, 360
Kohlrabi, artificial selection of, 13*f*
Kombu, 310
Komodo dragons, reproduction by, 120–21
Krabbe's disease, 210
Krebs cycle. *See* Citric acid cycle
Krill, 390
Kudzu, biological control of, 415
Kwashiorkor, 489

L

Labels, food, 485, 488
Labia majora, **555**
Labia minora, **555**
Labor, childbirth and, **568**
Laboratory procedures, DNA technology, 235
Labrador retrievers, 144–45, 151, 156, 167

Lab rat, genome of, 230
lac operon, 201
Lactase enzyme, 37, 51, 81
Lactation, 568
Lactic acid, muscle fatigue as accumulation of, 101–2
Lactose. *See also* Lactose intolerance
  as disaccharide, 41
  gene regulation and digestion of, 201
  human adaptation to digest, 366
Lactose intolerance, 36–37, 51
Lakes, 380, 384, 393
Lamarck, Jean-Baptiste de, 245
Lambda phage, 189
Lampreys, 356
Lancelets, **354**–55*f*
Land, plant colonization of, 295, 316–18. *See also* Terrestrial biomes
Landfills, methane from, 398
Landscape ecology, **445**. *See also* Conservation biology
Landscapes, **445**
Land-use patterns, 445
Language, 366, 584–85
Large intestine, **484**
Larva, **338**
Larval stages
  amphibian, 357
  insect, 352
Larynx, 480, **510**
Laser-assisted in situ keratomileusis (LASIK) surgery, 591
Lateralization, brain, 585
Lateral line system, **356**
Latex condoms, 560–61
Law of independent assortment, **151**, 162*f*
Law of segregation, **148**
  chromosomal basis of, 162*f*
  genetic alleles on homologous chromosomes and, 149
  monohybrid crosses and, 148–49
  seven characters of pea plants and, 147*f*
Laws, in vitro fertilization and society's, 551
LDL (low-density lipoproteins) cholesterol, 158
Leaf beetles, biological control by, 414
Leaves, **609**
  arrangement of, 609*f*
  chloroplast pigments and colors of autumn, 112
  ethylene in dropping of, 634
  eudicot vs. monocot, 606
  modified, 617
  photosynthesis in chloroplasts of, 108–9*f*, 316–17
  structure of, 609
  tissue systems of, 611*f*
Lederberg, Joshua, 194
Leeches, 345*f*, **346**
Leeuwenhoek, Anton von, 306
Left atrium, heart, 498–99
Left hemisphere, brain, 585
Left ventricle, heart, 498–99
Legal issues, in vitro fertilization and, 551
Legumes, nitrogen fixation of, 442, 629
Lemba people, 237
Lemmings, population cycles of, 411
Lemurs, 268–69, 361–62*f*, 444
Lengthening, plant. *See* Elongation, plant
Lens, eye, **589**
Lenses, artificial, 591
Leopards, taxonomy of, 285*f*–86*f*
Leptin, weight gain and, 490–91
Leukemia, 210, 234, **505**
Leukocytes, **505**. *See also* White blood cells
Lewinsky, Monica, 226
Lichens, **332**, 436
Life, **4**. *See also* Organisms
  biology as scientific study of, 4, 14 (*see also* Biology; Science)
  biology in everyday, 2–3, 15–16, 18
  Charles Darwin's theory of evolution of, by natural selection, 10–13 (*see also* Evolution; Natural selection)
  dependence of, on water, 22–23, 29–33 (*see also* Water)
  distribution of, in biosphere, 376
  evolutionary trees representing history of, 255
  explosive diversifications of, after mass extinctions, 284
  grouping of diversity of, in taxonomy of, 8–9 (*see also* Biodiversity; Taxonomy)
  hypotheses on origins of, 296–98
  levels of, 4–8
  major episodes in history of, 294–95
  microbial (*see* Microbial life)
  properties of, 4–5*f*
  spontaneous formation of membranes in origin of, 87
  synthesis of artificial, by synthetic biology, 293
  this book about evolution of, 17
  three domains of, 9 (*see also* Archaea; Bacteria; Eukaryotes)
  unity in diversity of, 9
  water and the search for extraterrestrial, 33
Life cycles, **131**
  alternation of generations in, 320
  angiosperm, 325–26, 617–21
  animal, 338
  effects of global climate change on, 397
  of sexual organisms, 131
Life histories, **406**–7
Life spans, plant, 613
Lifestyle changes
  avoidance of mutagens with, 187
  cancer prevention or survival with, 129, 214
Life tables, **406**
Ligaments, 459, **594**
Light. *See also* Light reactions; Sunlight
  electromagnetic spectrum of, 110–11
  energy of (*see* Solar energy)
  human eye and, 589
  phototrophs and, 302
  ultraviolet (*see* Ultraviolet (UV) light)
  visible, 111
Lightbulbs, energy-efficient, 398
Light microscope (LM), **56**–57
Light reactions, **110**–14
  chloroplast pigments in, 112
  electromagnetic spectrum of solar radiation and, 110–11
  generation of ATP and NADPH by, 113–14
  harvest of light energy by photosystems in, 112–13
  wavelengths (colors) of light and, 111
Lignin, **317**, 318, **612**
Limiting factors, population growth, **409**, 410–11
Linear structures, 40
Linkage maps, **164**
Linked genes, **163**–64
Linnaeus, Carolus, 285, 288
Linoleic acid, 488
Lionfish, 402*f*–3
Lions, taxonomy of, 285*f*
Lipids, **43**–45
  fats as, 43–44
  in plasma membranes, 60
  steroids as, 45
  synthesis of, by smooth ER, 65
Lipid-soluble hormones, 536–37
Liposomes, nanotechnology and creation of, 87
Liquid state of matter, 24
Liver, 479, **482**
Lizards
  physiological responses of, to environmental conditions, 378
  reproduction by, 120–21
  as reptiles, 358
Lobe-finned fishes, **356**–57*f*
Lobes, cerebral cortex, 584
Lobster anatomy, 347*f*
Lobsters, 349
Local biogeochemical cycles, 440
Locomotor systems, 593–99
  integration of stimulus and response in, 599
  movement as locomotor response in, 593
  muscular system and, 596–98
  skeletal system and, 594–95
Locus (loci), gene, **149**
Logic, scientific method and, 15
Logistic population growth model, **409**, 412–13
Long-night plants, 636–37*f*
Loose connective tissue, **458**–59
Lorises, 361
Lost Colony of Roanoke case study, 616
Low-density lipoproteins (LDL) cholesterol, 158
LSD, 580
Lung cancer
  DNA profiling of patients with, 233
  smoking and development of, 198–99, 513
Lungfishes, 356
Lungs, **508**–13. *See also* Respiratory systems
  cardiovascular system and, 497–98
  effects of smoking on human, 510, 512–13 (*see also* Lung cancer)
  in exchanges with external environments, 464–65
  respiratory surfaces of, 508
Luteinizing hormone (LH), 540, 557, 558–59
Lyell, Charles, 247
Lyme disease, 300, 304
Lymph, **520**–21
Lymphatic systems, 463*f*, **520**–21
Lymph nodes, **520**–21
Lymphocytes, **521**–27. *See also* B cells; T cells
  B cells and humoral immune response of, 526
  B cells and T cells as, 521
  clonal selection and multiplication of effector cells during primary immune response of, 524
  memory cells and secondary immune response of, 525
  recognition of antigens by antibodies and, 522
  T cells and cell-mediated immune response of, 526–27
  vaccination and, 525
Lynxes, population cycles of, 411
Lysogenic cycle, bacteriophage, **188**–89

Lysosomal storage diseases, 66
Lysosomes, 59, **66**
Lytic cycle, bacteriophage, **188**–89

M

Macaques, 361
McGuire, Mark, 534–35
Macroevolution, **278**–85
  by adaptation of old structures to new functions, 278
  case study on dinosaur mass extinction by meteor impact and, 284–85
  evo-devo and, by developmental processes, 279
  geologic time scale of fossil record and, 280–82
  mass extinctions and, 284
  plate tectonics and, 283
Macromolecules, **39**. *See also* Biological molecules; Polymers
Macronutrients, plant, **626**–27
Madagascar, 444
Mad cow disease, 48, 194
Magnetic resonance imaging (MRI), 31–32, 212*f*
Magnetoreception, 575, 588
Magnification, microscope, **56**–57
Major depression, 580, **586**
Malaria
  as caused by apicomplexan parasite, 308
  evolution of resistance to eradication of, 242–43
  insects as carriers of, 352
  sickle-cell hemoglobin as evolutionary response to, 265, 366
Malaysian horned frog, 357*f*
Males
  evolution of steroid hormones and aggression in, 547
  hermaphrodites and, 553
  sexual dimorphism and, 264
Males, human
  abnormal numbers of sex chromosomes in, 140
  DNA profiling of ancestry of, 237
  evolution of steroid hormones and aggression in, 547
  infertility of, 568–69
  reproductive anatomy of, 554
  sex chromosomes of, 165
  sex hormones of, 546
  sex-linked disorders in, 165–66
Malignant tumors, **129**, 212–13. *See also* Cancer
Malleus, ear, 592
Malnutrition, **489**
Maltose, 41
Mammals, **360**
  adaptations of, to environmental variability, 378–79
  as amniotes, 358
  applications of genetically modified cells of, 221
  characteristics of, 360
  diversification of, after dinosaur mass extinction, 284, 289
  emergence of, in history of life, 295
  evolution of traits of, 10
  extinctions of species of, 426
  geographic distribution of, as evidence of evolution, 249
  number of chromosomes in cells of, 123*f*
  primates and humans as, 361 (*see also* Humans; Primates)
  reproductive cloning of, 208–9
  sex chromosomes and sex-linked genes of, 165–66
Mammary glands, 360
Mandrills, 361
Manic-depressive disorder, 586
Mantises, praying, 351*f*, 637
Mantle, **343**
Maple syrup, 630
MAPs (morning-after pills), **560**
Maps, linkage, **164**
Marathoners vs. sprinters, 90–91
Marijuana, 580
Marine biomes, 380, 382–83, 468–69. *See also* Biomes
Marine fisheries, 413, 428
Mars, water on, 33
Mars Global Surveyor, 33
Marshall, Barry, 481
Marshes, 381, 383, 424–25
Marsupials, 249, 283, **360**
Mass, **25**
Mass extinctions. *See also* Extinctions
  of dinosaurs, 284–85, 289, 358
  explosive diversifications of life after, 284, 289
  humans and sixth, 268–69
Mass number, 24*f*, **25**
Mast cells, 528
Master control genes. *See* Homeotic genes
Maternal age, Down syndrome and, 139
Maternal care, evolution of menopause for, 570
Mating. *See also* Sexual reproduction; Sexual selection
  hybridization and interspecies, 273
  sexual selection in, 264
Matrix, bone, 595
Matrix, mitochondrial, **68**
Matter, composition of, **24**–25
Measles/mumps/rubella (MMR) vaccination, 525
Measles virus, 190
Measurements, science and, 14, 17
Mechanical defenses, predation and, 430
Mechanical digestion, 477, 479
Mechanical energy, mechanoreceptors of, 588
Mechanical isolation, 273
Mechanical work, cellular, 79
Mechanoreceptors, 574–75, **588**
Medicine. *See also* Diseases and disorders, human
  antibiotic-resistant bacteria and (*see* Antibiotic-resistant bacteria)
  antibodies in, 522
  bioprospecting and, 426
  cancer treatments, 129
  cardiovascular disease and, 506
  cochlear implants to correct hearing, 593
  contraception methods, 559–60
  defibrillators and artificial pacemakers in, 500
  dialysis and kidney replacement in, 470
  DNA profiling of lung cancer patients, 233
  drugs in (*see* Drugs)
  genetic engineering in, 220–22
  genomics in, 231, 233
  health science and, 259
  HIV/AIDS treatments, 193
  human gene therapy, 234
  impact of loss of plant diversity on, 327
  leeches in, 345*f*–46
  malaria treatments, 243
  radioactive isotopes in, 26
  reproductive cloning in, 208–9*f*
  reproductive technologies (*see* Reproductive technologies)
  for skeletal diseases and injuries, 595
  surgery in (*see* Surgery)
  therapeutic cloning in, 210
  umbilical cord blood therapy, 210
  vision correction, 591
Mediterranean biome, 388
Medulla oblongata, **583**
Medulloblastoma (MB), 212
Medusa form, **342**
Meiosis, **132**
  chromosomal basis of inheritance and, 162–64 (*see also* Chromosomal basis of inheritance)
  errors in, 138–40
  in life cycles of sexual organisms, 131
  mitosis vs., 134–35
  nondisjunction errors during, 138
  origins of genetic variation in, 135–37, 258
  stages of, 132–33
  trisomy 21 errors in, and Down syndrome, 139
Melanoma, 214. *See also* Cancer
Membrane proteins, 60, 83*f*
Membrane structure. *See* Plasma membranes
Memory cells, 524–**25**
Men. *See* Males, human
Mendel, Gregor, **146**. *See also* Mendelian inheritance
  Charles Darwin and, 256
  experiments of, 146–47
  law of independent assortment by, 150–51
  law of segregation by, 147–49
Mendelian inheritance, 144–71. *See also* Inheritance
  chromosomal basis of (*see* Chromosomal basis of inheritance)
  dog breeding and, 144–45, 157, 167
  dominant human genetic disorders in, 156
  extensions to Mendel's laws in, 158–61
  family pedigrees in, 153–54
  genetic testing and, 157
  human ABO blood groups and codominance in, 159
  incomplete dominance in plants and people in, 158
  law of independent assortment in, 150–51
  law of segregation in, 147–49
  Gregor Mendel's experiments and, 146–47 (*see also* Mendel, Gregor)
  polygenic inheritance in, 160–61
  recessive human genetic disorders in, 154–56
  role of environment in, 161
  rules of probability in, 152–53
  sickle-cell disease and pleiotropy in, 160
  synthesis of Darwinism and (*see* Modern synthesis)
  testcrosses to determine unknown genotypes in, 152
Meninges, **582**
Meningitis, 230, 303, 582
Menopause, grandmother hypothesis on evolution of, 570

Menstrual cycle, 540, **558**–59
Menstruation, 512, 555, **558**–59
Mental retardation, phenylketonuria and, 259
Mercury, biological magnification of, 433
Meristems, **613**–14
Mescaline
  effects of, on human brain, 580
  as herbivory defense, 431
Mesoderm, 340, 563
Mesophyll, **611**
Mesozoic era, 280–81*f*, 358
Messenger RNA (mRNA), **182**
  in DNA microarrays, 206–7
  in gene expression, 63, 182
  gene regulation of lifetime of, 204
  in gene synthesis for recombinant DNA technology, 225
  processing of, after transcription, 182
Metabolic pathway, cellular respiration as, 96. *See also* Cellular respiration
Metabolic rate, **485**, 541
Metabolism, **80**. *See also* Cellular work
Metamorphosis, **338**
  amphibian, 357
  insect, 352
  sea star, 338
Metaphase, mitosis, **127**, 134*f*
Metaphase I, meiosis I, 132*f*, 134*f*, 135–36
Metaphase II, meiosis II, 133*f*
Metastasis, cancer, **129**
Meteorites
  dinosaur mass extinction by impact of, 284–85
  in origin of life, 297
Methane
  alternative representations of, 27*f*
  as hydrocarbon, 38
  from landfills and cattle, 398
Methanogens, 303
Methicillin-resistant *Staphylococcus aureus* (MRSA), 18, 61
Methionine (Met), 180, 184
Methylphenidate, 580
Mexico, age structure and population momentum in, 418
Microbial life, 292–313
  abiotic formation of biological monomers for, 297
  complement proteins as innate defense against, 519
  evolution of multicellular life from unicellular, 311
  hypotheses on origins of, 296–98
  major episodes in history of, 294–95
  origins of, 292–93, 297, 311
  prokaryotes, 299–305 (*see also* Prokaryotes)
  protists, 306–11 (*see also* Protists)
  synthesis of artificial, by synthetic biology, 293
Microevolution, **259**–62. *See also* Evolution
  as evolution of population gene pools, 259
  mechanisms of, 260–62 (*see also* Natural selection)
Microfilaments, cytoskeleton, 69
Micrographs, 56*f*
Micronutrients, plant, **626**–27
MicroRNAs (miRNAs), 204
Microscopes, 56–57
Microtubules, **69**, 69
Microvilli, small intestine, 483
Midbrain, 583
Middle ear, **592**–93
Mifepristone, 560
Migration
  of elephants, 574
  as evolutionary adaptation to environmental variability, 378–79
  gene flow from, 262
  by *Homo erectus*, 364
  by *Homo sapiens*, 366
  movement corridors for, 445
  as thermoregulation adaptation, 471
  in tundra biome, 390
Milk
  lactation of, 568
  lactose digestion and, 41, 201, 366
  lactose intolerance and, 36–37, 51
Miller, Jerry, 17*f*
Miller, Stanley, 297
Millipedes, **350**
Mimicry, predation and, 430–31
Minerals, human nutrition and, **488**
Minerals, plant nutrition and, **626**. *See also* Nutrients, inorganic
Mining
  bioremediation of sites of, 305
  habitat destruction by mountaintop removal in, 427*f*
miRNAs (microRNAs), 204
Miscarriage, 565, 569
Misfolded proteins, diseases and, 48
Missense mutations, 186
Mites, 348*f*
Mitochondria, **68**
  electron transport in, 99
  emergence of, in history of life, 294
  energy conversion in cellular respiration by, 68
  evolution of, from symbiotic prokaryotes, 306
  in human sperm, 562
Mitosis, **125**–28
  cytokinesis and, 125, 127*f*–28
  in life cycles of sexual organisms, 131
  meiosis vs., 134–35
  phases of, 126–27
Mitotic (M) phase, cell cycle, **125**–28
Mitotic spindles, **127**
Mixotrophs, protist, 307
Model organisms
  garden peas as, 146
  genomes of, 230
Models, population growth, 408–9. *See also* Population growth
Modern synthesis, **256**–59
  gene pool analysis in, 258–59
  genetic variation in populations in, 257–58
  microevolution as changes in gene pools in, 259
  population genetics and health science in, 259
  populations as units of evolution in, 256–57
Modified leaves, 617
Modified roots, 607*f*
Modified stems, 608*f*
Molds, fungal, 328*f*
Molecular biology, **174**
  bioinformatics in, 232
  evidence for evolution in, 251
  evidence for speciation in, 270
  as molecular study of heredity, 174
  as tool in molecular systematics, 287
Molecular formulas, 27*f*
Molecular systematics, 287
Molecules, **27**. *See also* Compounds
  alternative ways to represent, 27*f*
  covalent bonds and, 27–28
  of DNA in genes, 7–8
  hydrophilic and hydrophobic (*see* Hydrophilic molecules; Hydrophobic molecules)
  large biological (*see* Biological molecules)
  as level of life, 5*f*
  neurotransmitters as, 580
  passive transport of, across membranes, 83–85
  polar, 28
Molluscs (Mollusca), **343**
Molting, arthropod, 347, 352
Monarch butterflies, 351*f*
Mongoose, impacts of biological control by, 414
Monkeys, 361–62*f*
Monocots, **606**
Monoculture agriculture, 416
Monod, Jacques, 201
Monohybrid crosses, **148**–49
Monomers, **39**
  abiotic synthesis of, in origin of life, 296–97
  amino acids as, of proteins, 46
  as components of polymers, 39
  nucleotides as, of nucleic acids, 49–50
Monosaccharides, **40**
Monotremes, **360**
Monozygotic twins, 563
Montagnier, Luc, 523
Mood swings
  bipolar disorder and, 586
  steroids and, 546
Morgan, Thomas Hunt, 163–64
Morning-after pills (MAPs), **560**
Morphine
  effects of, on human brain, 580
  as herbivory defense, 431
Mortality. *See also* Death rates
  cancer and rates of human, 214
  cardiovascular disease, 506
  flu vaccines and rates of human, 192
  high-altitude genetic adaptations and infant, 513
Mosquitoes, malaria and, 243, 253
Mosses, **318**–20, 436
Motor cortex, brain, 584
Motor neurons, **576**, 582, 598
Motor output, nervous system, **576**
Motor proteins, 79*f*
Motor systems, **582**
Motor units, **598**
Mouflon sheep, 208–9*f*
Mountain ranges, climates and, 384–85
Mountain sickness, 513
Mountaintop removal mining, 427*f*
Mouth, 478–**79**
Movement, cell
  cilia and flagella in, 70
  microtubules in, 69
Movement corridors, **445**. *See also* Migration
Mozambique tilapia, male aggression in, 547
MRI. *See* Magnetic resonance imaging (MRI)
MRSA (methicillin-resistant *Staphylococcus aureus*), 18, 61
Mucus
  as external innate defensive barrier, 518
  stomach, 481
Mudflats, 383
Mules, reduced hybrid fertility of, 273

Multicellular organisms
  emergence of, in history of life, 294–95
  evolution of, from unicellular colonial protists, 311
  exchanges with external environments by, 464
  single-celled organisms vs., 56
Multiple sclerosis (MS), 529, 577
Multiplication, rule of, **152**–53
Mummified humans, DNA profiling of, 227
Mumps virus, 190–91
Murder investigation. *See* Forensics
Muscle fibers
  skeletal muscle, 596–98
  slow-twitch vs. fast-twitch, 91
Muscles
  in blood flow through blood vessels, 501–2
  in breathing, 511
  cellular respiration in, 90–91
  control of contraction of, by motor units, 598
  effector cells, motor neurons, and motor output of, 576
  fermentation in, 101–2
  motor systems and, 582
  muscle tissue and types of, 460
  sliding filament model of contraction of, 596–97
  thermoregulation by contraction of, 468
Muscle tissue, **460**
Muscular dystrophy, 165
Muscular system, **596**–98
  control of muscle contraction by motor units in, 598
  sliding-filament model of muscle contraction in, 596–97
  vertebrate, 462*f*
Mushrooms, 329, 331–32. *See also* Fungi
Mussels, 343, 435
Mustard plant
  genome of, 230
  vegetable plants as descendents of, 12–13*f*
Mutagenesis, 187
Mutagens, **187**
Mutations, **186**
  in anthrax killer investigation, 231
  cancers caused by, 129, 211–15
  childhood tumors caused by, 212
  in development of lung cancer, 199
  in emergence of new senses, 598
  emerging viruses and, 194
  in evolution of pre-cells to cells, 298
  in evolution of ultraviolet vision in birds, 599
  during gene expression, 186–87
  high-altitude adaptations from, 513
  of HIV, 530
  in macroevolution by developmental processes, 279
  mutagens causing, 187
  in prokaryotic reproduction, 301
  in sickle-cell hemoglobin as evolutionary response to malaria, 265
  as source of genetic variation, 257–58
  sympatric speciation and, 276
  types of, 186–87
Mutualism, **430**
  of soil bacteria and plants, 442, 628–29
  symbiosis and, 430 (*see also* Symbiosis)
Mycelium, **329**
Mycoplasma capricolum, 293
Mycoplasma mycoides, 293
Mycorrhizae, **316**, **628**
  as mutualism, 430
  as plant-fungus symbiosis, 316, 328, 628, 637
Myelin sheath, **576**–77
Myocardial infarctions, 506. *See also* Heart attacks
Myofibrils, **596**–98
Myopia, 591
Myosin, 596
Myrothecium verrucaria, 415

N

NAD^+ (nicotinamide adenine dinucleotide), 95–101
NADH, **95**–101
$NADP^+$, 110
NADPH, **110**, 113–15
Nanotechnology. *See also* DNA technology; Genetic engineering
  engineering of enzymes with, 81
  evolution of membranes and, 87
  harnessing cellular structures with, 75
National Aeronautics and Space Administration (NASA), 33
National Center for Biotechnology Information, 232
National Institutes of Health (NIH), 236, 546
National Oceanic and Atmospheric Administration (NOAA), 403
Natural disturbances. *See* Disturbances
Natural family planning, **559**–60
Natural gas, 321
Natural killer (NK) cells, **519**
Natural phenomena, science and, 14
Natural selection, 11–**12**, **244**
  basis of Charles Darwin's theory on, 252–53
  Charles Darwin's theory of evolution by, 10–13 (*see also* Evolution)
  descent with modification theory as, 10, 244, 247
  evolutionary adaptation by, 11–13, 244–45, 262–64, 378–79 (*see also* Evolutionary adaptations)
  evolution of alternative photosynthetic pathways by, 116
  in evolution of antibiotic-resistant bacteria, 18, 71
  in evolution of pre-cells to cells, 298
  in evolution of ultraviolet vision, 599
  global climate change as agent of, 399
  life history traits and, 407
  of lizard horn length as response to predation, 254
  modern examples of, 253–54
  in origin of plants from green algae, 318
  as scientific theory, 17
  sexual selection as form of, 264
  three modes of, 263–64
Nature vs. nurture, inheritance and, 161
Nautilus, 343*f*
Neanderthals, 233, 365
Nearsightedness, **591**
Near vision, 589*f*
Necrotizing fasciitis, 61
Nectar, flower, 621
Negative blood types, 159
Negative feedback, **466**
Negative pressure breathing, **511**
Nematodes (Nematoda), 230, **346**
Nephrons, urinary system, **469**–70
Nerve cells, 461
Nerve gases, enzyme inhibition of, 82
Nerves, **576**
Nervous systems, 574–75, **576**–602
  brains in, 583–86
  central nervous system (CNS) of, 581–82
  divisions and functions of, 576
  effects of drugs on the brain in, 580
  emergence of new senses and, 598 (*see also* Senses)
  extrahuman senses and, 574–75, 588, 592, 598–99
  integration of, with locomotor response, 599
  locomotor systems and, 593–99 (*see also* Locomotor systems)
  neurons in, 576–77
  neurotransmitters in, 580
  overview of, 576–80
  peripheral nervous system (PNS) of, 582
  propagation of signals in, 578
  resting potentials and action potentials in, 577
  senses and, 587–93 (*see also* Senses)
  signal transmission through neurons in, 577–78
  transmission of signals from neurons to receiving cells in, 579–80
  vertebrate, 463*f*
Nervous tissue, **461**
Neurological disorders, 586
Neurons, **461**, **576**
  autonomic nervous system, 582
  functions of, in nervous systems, 576
  in nervous tissue, 461
  signal transmission through, 577–78
Neurospora crassa (bread mold), 178
Neurotransmitters, **579**
  disorders of, 580
  in hearing, 593
  in muscle contraction, 598
  in nervous system signal transmission, 579–80
  in sensory transduction, 587–88
Neutrons, **25**–26
Newcomb, Jim, 17*f*
New Orleans, phytoremediation in, 625
New World monkeys, 361–62*f*
Niall of the Nine Hostages, 237
Nicotine
  effects of, on human brain, 580
  as herbivory defense, 431
Night length, plant responses to, 636–37*f*
Night vision, 590
Nile crocodile, 359*f*
Nitrate, soil bacteria and, 628–29
Nitrifying bacteria, 628
Nitrogen (N)
  in composition of human bodies, 24
  deficiencies of, in plant nutrition, 627
  in ecosystem chemical cycling, 437
  electron arrangement of, 26
  in fertilizers, 627
  in freshwater pollution, 393
  soil bacteria and, for plant nutrition, 442, 628–29
Nitrogen fixation, **442**, **628**
Nitrogen-fixing bacteria, 628–29

Nitrogen gas (N_2)
conversion of, by soil bacteria for plant nutrition, 628–29
in nitrogen cycle, 442
Nitrogenous bases, DNA and RNA, 7–8, 49–50, 174–76, 179
Nitrous oxide pollution, 442
NK (natural killer) cells, **519**
Nobel Prize winners
A. V. Hill, 102
Joshua Lederberg, 194
Barry Marshall, 481
Luc Montagnier, 523
James Watson, Francis Crick, and Maurice Wilkins, 177
Nodes, stem, **608**
Noncoding DNA, 182, 228, 230–31
Nondisjunction, meiosis, **138**–40
Nonidentical twins, 563
Non-insulin-dependent diabetes, 544. *See also* Diabetes mellitus (diabetes)
Nonself vs. self proteins, 526–27, 529
Nonsense mutations, 187
Norepinephrine (noradrenaline), **544**
adrenal gland production of, 544–45
autonomic nervous system and, 582
as neurotransmitter, 580
Nori, 310
Nostril hairs, 518
Notochord, **354**
Novelty, evolution of biological. *See* Macroevolution
N-P-K fertilizer ratio, 627
Nuclear disasters
Chernobyl nuclear reactor explosion, 26
Fukushima nuclear disaster, 26, 624–25
Nuclear envelope, **62**, 64
Nuclear transplantation, **208**. *See also* Reproductive cloning
Nucleic acid probes, **224**–25
Nucleic acids, **49**
abiotic synthesis of, in origin of life, 297
DNA and RNA as, 174–75 (*see also* DNA (deoxyribonucleic acid); RNA (ribonucleic acid))
as macromolecules, 39
protein synthesis by, 48–50 (*see also* Gene expression)
in viruses, 188
Nucleoid, **58**
Nucleolus, **62**
Nucleosomes, DNA, **124**
Nucleotide insertion or deletion mutations, 186–87
Nucleotides, **49**, **174**
in gene expression, 179
as monomers of nucleic acids, 49–50, 174–75
Nucleotide substitution mutations, 186–87
Nucleus (nuclei), **25**, **58**
in eukaryotic cells, 7, 58
nucleic acids in, 49
reproductive cloning by transplantation of, 208 (*see also* Reproductive cloning)
structure and function of, 62
in structure of atoms, 25
Nurses' Health Study, 16
Nurture vs. nature, inheritance and, 161
Nutrient absorption, human, 482–83
Nutrients, inorganic, 626–27
as abiotic factors in biosphere, 377
chemical cycling of (*see* Chemical cycling)
in freshwater biomes, 380
in human diets, 488
nutrient pollution by excess, 443
Nutrition, animal, 476–78
Nutrition, human, 474–93
animal nutrition and, 476–78
digestive system and, 479–84
disorders of, 489–91
requirements for, 485–88
weight control and, 474–75, 481, 485, 490–91
Nutrition, plant, 626–31
absorption of water and nutrients from soil by roots in, 628
essential elements for, 626–27
fertilizers for, 627
role of bacteria in nitrogen acquisition in, 628–29
sugar transport in, 630–31
water transport in, 629–30
Nutritional disorders, human, 489–91. *See also* Nutrition, human
eating disorders, 489
evolutionary basis for fat and sugar cravings, 491
malnutrition, 489
obesity, 490–91
Nutritional modes. *See also* Trophic structures
animal, 338
in ecosystems, 6, 92
eukaryotic, 289
fungal, 329
prokaryotic, 302
protist, 307
Nutritional requirements, human, 485–88. *See also* Nutrition, human
essential nutrients, 486–88
food calories and basal metabolic rate, 485
food labels and, 488

O

obese gene case study, 490–91
Obesity, **490**
evolutionary basis of, 491
genetic basis of, 490–91
as overnourishment nutritional disorder, 490
weight control and, 474–75, 481, 485, 490–91
Observations, science and, 14–17. *See also* Case studies
Occipital lobe, cerebral cortex, 584
Ocean acidification
carbon dioxide and, 33, 395
effects of, on coral reefs, 383
Oceans, 382–84
acidification of (*see* Ocean acidification)
effects of, on climate, 384
as marine biomes, 382–83
Octane, 38–39*f*. *See also* Fossil fuels
Octopuses, 343
Offspring, overproduction of, 11, 252–53
Oil spills. *See also* Fossil fuels
economic costs of, 425
effects of, on marine biomes, 383
prokaryotic bioremediation of, 305
Old World monkeys, 361–62*f*
Omega-3 fatty acids, 44, 222
Omega-6 fatty acids, 488
Omnivores, **434**, **476**
Oncogenes, **211**–12. *See also* Cancer
One gene–one enzyme hypothesis, 178
On the Origin of Species by Means of Natural Selection (book), 10–13, 146, 244, 247, 270, 289
Oogenesis, **556**
Open circulatory systems, **496**
Open systems, organisms as, **464**
Operators, DNA, **201**
Operculum, **356**
Operons, DNA, **201**
Opiates, 580
Opossums, 360
Opportunistic life histories, **407**, 416
Optic nerve, **589**
Oral cancer, 129
Oral cavity, **479**
Oral contraceptives, 560
Orange-crowned warblers, 429
Orange fungi, 328*f*
Orangutans, 361*f*–62*f*
Order, as property of life, 4
Orders (taxonomy), **286**
Organelles, **58**
destruction of damaged, by lysosome enzymes, 66
of endomembrane system, 64–67
energy conversion by, 68
in eukaryotic cells, 58, 59
as level of life, 5*f*
Organic compounds, **38**. *See also* Biological molecules
carbon chemistry of, 38–39
heterotrophs and, 302
macromolecules of, as polymers of monomers, 39
for plant nutrition, 626–27
Organic farming, **627**, 634. *See also* Agriculture
Organic fertilizers, 627
Organismal ecology, **375**
Organisms, **375**. *See also* Life
communities of (*see* Communities)
as composed of cells, 7, 56 (*see also* Cells)
determination of phenotypes of, from genotypes of, 178
evolutionary adaptations of, to environmental variability, 378
fungi as Earth's oldest and largest, 329 (*see also* Fungi)
history of, on Earth, 294–95
interdependence of, 624–25, 633, 637
as level of life, 5*f*
life cycles of sexual, 131
model (*see* Model organisms)
as open systems, 464
organismal ecology and, 375
phenotypes of, vs. genotypes of, 149
plate tectonics and geographic distribution of, 283
populations of (*see* Populations)
sequencing of genomes of, 8, 230–33 (*see also* Genomes; Genomics)
synthesis of artificial, by synthetic biology, 293
three domains of, 9, 286 (*see also* Archaea domain; Bacteria domain; Eukarya domain)
Organizational hierarchy, animal body, 456. *See also* Animal structure and function
Organ of Corti, 592–93

Organs, animal, **461**
reproductive cloning of, 208–9*f*
tissues of, 461
Organs, as level of life, 5*f*. *See also* Organs, animal; Organs, human; Organs, plant
Organs, human
autonomic nervous system and, 582
bones as, 595
of digestive system, 479–84
embryonic development of, 563–64
epithelial tissue in linings of, 458*f*
organ systems of, 462–63
Organs, plant, **607**–9
leaves, 609
roots, 607
stems, 608
tissues of, 610
Organ systems, **462**
autonomic nervous system and, 582
in exchanges with external environments, 465
as level of life, 5*f*
organs and functions of, 462–63
Origin of Species, The (book), 10–13, 146, 244, 247, 270, 289
Origins of replication, DNA, 177
Oryza sativa genome, 230
Osmoconformers, **468**–69
Osmoregulation, animal, **85**, **468**–69
Osmoregulators, **468**–69
Osmosis, **84**
in animal osmoregulation, 468–69
water balance and, 84–85
Osteoporosis, 488, **595**
Ostriches, 359
Otitis media, 592
Outer ear, **592**
Outgroups, cladistics and, 287–88
Ova, 556. *See also* Eggs
Ovarian cycle, human, **558**–59
Ovaries, flower, **324**, **617**, 620
Ovaries, human, **555**
endocrine system functions of, 539*t*, 546
reproductive functions of, 555
Overconsumption, ecological footprints and, 420
Overexploitation
declining biodiversity through, 428
overgrazing, 419
overharvesting of fish, 413
Overnourishment. *See* Obesity
Overproduction, natural selection and, 11, 252–53. *See also* Reproduction
Overweight. *See* Obesity; Weight control, human
Oviduct, **555**, 557, 564
Ovulation, **555**, 557
Ovules, **323**, **617**
angiosperm, 324*f*, 617, 619
gymnosperm, 323
Oxidation, **95**
Oxidation-reduction (redox) reactions, **95**
Oxygen (O). *See also* Oxygen gas (O_2)
in composition of human bodies, 24
electron arrangement of electrons of, 26
Oxygen gas (O_2). *See also* Oxygen (O)
as abiotic factor in aquatic biomes, 377
in aerobic lifestyles, 91 (*see also* Aerobic vs. anaerobic lifestyles)
alternative representations of, 27*f*
animal exchange of carbon dioxide and (*see* Circulatory systems; Respiratory systems)
case study on high-altitude athletic training and, 504
in cellular respiration, 77–78, 94–96
in chemical cycling between photosynthesis and cellular respiration, 92–93
depletion of, in freshwater biomes, 380
evolution of glycolysis in absence of, 103
human exchange of carbon dioxide and (*see* Cardiovascular systems)
nutrient pollution and depletion of, 443
oxygen revolution in history of life, 294
in photosynthesis, 108–9
red blood cells and, 503–4
in redox reactions, 95
Oxytocin, 568
Oysters, 343

P

p53 gene, smoking, lung cancer, and, 199
Pacemaker, heart, **500**
Pace patterns, speciation, 277
Paclitaxel, 129
Paedomorphosis, macroevolution and, **279**
Paine, Robert, 435
Pain receptors, **588**
Paleontology, 10*f*, 248
Paleozoic era, 280–81*f*
Palmeiro, Raphael, 535
Palm oil, biofuels and, 392
Pancreas, **482**, **543**
digestive system functions of, 479, 482
endocrine system functions of, 538–39*t*, 543–44
Pandemic, H1N1 influenza virus, 173
Pangaea, 283
Panthera genus, 285–86
Panting, thermoregulation and, 471
Pantothenic acid, 98
Pan troglodytes genome, 232
Papaya ringspot potyvirus (PRSV), 190
Pap tests, 555
Paramecium, 56*f*, 67*f*, 70*f*, 308, 429
Paranthropus, 364
Paraplegia, 581
Parasites, **307**, **432**
in community ecology, 432
flatworms as, 344
fungi as, 330, 426
lampreys as, 356
protists as, 307, 308
roundworms as pests in, 346
Parasympathetic division, autonomic nervous system, **582**
Parathyroid glands, 539*t*, **542**
Parathyroid hormone (PTH), **542**
Parenchyma cells, **612**
Parental care
evolution of menopause for, 570
in life histories, 407
Parietal lobe, cerebral cortex, 584
Parkinson's disease, 48, 231, 580
Paroxetine, 586
Parthenogenesis, 121
Partially hydrogenated vegetable oil, 44
Passive transport, 83–**84**
Pasteur, Louis, 296
Patas monkey, 362*f*
Paternity, DNA profiling and, 226
Pathogens, **303**, **518**
bacterial, 303–4
in community ecology, 432
defenses against, 518–19 (*see also* Adaptive defenses; Immune systems; Innate defenses)
human-caused disturbances and, 436
Paxil, 586
PCBs, biological magnification of, 433
Peas, Gregor Mendel's study of, 146–51. *See also* Mendelian inheritance
Peat moss, 319*f*
Pedigrees, **153**–54
Peistocene extinctions, humans in, 421
Pelagic realm, **382**
Pelvic inflammatory disease (PID), 560
Penguins
effects of global climate change on, 373, 399
as flightless birds, 359
in polar ice biome, 390
population ecology and, 404*f*
Penicillin, 55, 71, 82, 332
Penile implants, 569
Penis, **554**
Peppermint, as herbivory defense, 431
Pepsin, **480**, 482
Peptide bond formation, **184**
Peptide bonds, amino acid, **47**
Peptide hormones, 537
Peptide neurotransmitters, 580
Perennials (plants), **613**
Periodic table of elements, 24
Peripheral nervous system (PNS), **576**, 582
Peristalsis, **480**, 484
Permafrost, **390**
Permian mass extinction, 284
Personal genetic testing kits, 236–37
Personal genomics, 233
Pesticides
biological magnification of, 433
as enzyme inhibitors, 82
evolution of resistance to, 243, 253
synthetic, 416
toxins as herbivory defenses and, 431
Pests
biological control of, 414
integrated pest management and, 416
pesticides for (*see* Pesticides)
Petals, flower, **324**, **617**
Petioles, **609**
PET scanners, 26
P generation, **147**
pH scale, **32**–33. *See also* Acids; Bases, acids and
Phages, **188**–89
Phagocytic cells, **519**–20, 526
Phagocytosis, **86**, 478
Pharmaceutical (pharm) animals, 222
Pharmaceutical drugs. *See* Drugs
Pharyngeal slits, **354**
Pharynx, **480**, **510**
Phenotypes, **149**
family pedigrees of, 153–54
gene expression as determination of, from genotypes, 178
genetic variation and, 257
genotypes vs., 149, 178
modes of natural selection of, 263–64
Phenylketonuria (PKU), 259
Phloem, **317**, **610**
in plant sugar transport, 630–31
primary and secondary, 614–16
as vascular tissue, 317, 610
Phloem sap, **631**
Phoenix Mars Lander, 33
Phosphate group, 49, 60, 174–75

Phosphate pollution, 443
Phosphate transfer, ATP cycle and, 79–80
Phospholipid bilayers, **60**, 87. *See also* Plasma membranes
Phospholipids, **60**, 87
Phosphorus (P)
  biogeochemical cycling of, 441
  in composition of human bodies, 24
  in fertilizers, 627
  in freshwater pollution, 393
Phosphorus cycle, 441
Photic zone, **380**, 382
Photoautotrophs, 302, 316
Photons, **112**
Photoperiods, plants and, **636**–37*f*
Photopsins, 590
Photoreceptors, **588**–90
Photosynthesis, **92**, 106–7, **108**–18
  bacterial, 300*f*
  biofuels from, 106–7
  C_4 plants and, 116
  CAM plants and, 116
  Calvin cycle of, 115–16
  in chemical cycling, 92–93, 440–43
  chloroplasts as sites of, 68, 108–9*f*
  in ecosystem energy flow, 437–39
  emergence of, in history of life, 294
  by endosymbionts, 306
  in freshwater biomes, 380
  green energy and, 106–7, 111, 115–16
  leaves as site of, 609
  light reactions of, 110–14
  in marine biomes, 382
  mesophyll as site of, 611
  overview of stages of, 110
  protist, 307, 310
  relationship between cellular respiration and, 109 (*see also* Cellular respiration)
  relative abundance of chlorophyll and global, 376
  simplified equation for, 109*f*
  as terrestrial plant adaptation, 316–17
  in trophic structure food chains, 432–33
  wavelengths (colors) of light driving, 111
Photosystems, **113**
  generation of ATP and NADPH by, 113–14
  harvest of light energy by, 112–13
Phototrophs, 302
Phototropism, **632**–33, 636
Phrynosoma mcalli, 254
Phyla (taxonomy), **286**
Phylogenetic trees, **286**–88. *See also* Evolutionary trees
Phylogeny, animal, 340–41*f*
Physiological responses to environmental conditions, 378
Physiological thermoregulation adaptations, 471
Physiology, **457**. *See also* Animal structure and function
Phytoplankton, **380**
  biological magnification and, 433
  in freshwater biomes, 380–81
  in marine biomes, 382
  in trophic structure food chains, 432–33
Phytoremediation, 624–25
Pigments
  chloroplast, 112
  human skin pigmentation, 366
  visual, 590
Pigs, genetically modified, 222
Pili, prokaryotic cell, 58
Pill bugs, 349*f*
Pine trees, 322–23
Pink eye, 589
Pinna, **592**–93
Pinworms, 346
Pisaster sea stars, 435
Pistils, 617
Pith, **610**
Pituitary gland, **540**
  endocrine system functions of, 538–41
  production of oxytocin by, 568
  stress responses of, 545
Pivot joints, **594**
Placenta, **360**, **565**, 568
Placental mammals, **360**
Placental stem cells, 210
Plague, 304
Planarians, 344
Plankton, **310**
Plantae kingdom, 9, 289
Plant growth, 613–16
  abscisic acid in, 635
  cytokinins in, 634
  gibberellins in, 635
  gravitropism and directional, 636
  lengthening in primary, 613–14
  photoperiod responses in, 636–37*f*
  phototropism in, 632–33, 636
  plant life spans and, 613
  thickening in secondary, 614–16
  tropisms in, 636
Plants, 314–15, **316**–27
  adaptations of, to environmental variability, 379
  altitude and vegetation types of, 384
  angiosperms, 324–26 (*see also* Angiosperms)
  artificial selection of, 12–13*f*
  asexual and sexual reproduction by, 140
  bryophytes, 319–20
  cancer chemotherapy drugs from, 129
  cell cyle of (*see* Cell cycle, eukaryotic)
  cells of, 59, 61 (*see also* Eukaryotic cells)
  central vacuoles in cells of, 67
  in chemical cycling, 92–93, 440–43
  cloning of, 207
  cohesion and water transport in, 29
  diversity of, as nonrenewable resource, 327
  ecological succession of species of, after disturbances, 436–37
  in ecosystem energy flow, 437
  essential amino acids in, 486
  Eukarya domain and Plantae kingdom of, 9, 289
  extinctions of species of, 426
  ferns, 321
  genetically modified (GM), 190, 221–22, 235–36
  gymnosperms, 322–23
  herbivory of, 431, 605
  highlights of evolution of, 318–19
  hormones of, 632–35 (*see also* Hormones, plant)
  incomplete dominance in, 158
  interdependence of organisms and, 624–25, 633, 637
  medicines derived from, 327*t*
  Mendelian inheritance and (*see* Mendelian inheritance)
  nutrition for, 626–31 (*see also* Nutrition, plant)
  origin of, from green algae, 318
  parasites and pathogens of, 432
  parasitic fungi and, 330
  as photoautotrophs, 302
  photoperiod responses of, 636–37*f*
  photosynthesis in (*see* Photosynthesis)
  phylogenetic tree of, 318*f*
  phytoremediation and bioremediation by, 447, 624–25
  polysaccharides in, 42
  populations of (*see* Populations)
  as producers, 9, 432 (*see also* Producers)
  reproductive adaptations of, 317
  responses of, to stimuli, 636–37
  structural adaptations of, 316–17
  symbiosis of fungi and, 314–15, 332, 430, 628, 637
  sympatric speciation and food, 276
  terrestrial adaptations of, 316–17, 322–23
  terrestrial biomes and vegetation types of, 385
  in trophic structure food chains, 432
  tropisms of, 636
  unsaturated fatty acids in oils of, 44
  viroids that infect, 194
  viruses that infect, 190
  water balance in cells of, 85
Plaque deposits, atherosclerosis and, 44, 506
Plasma, blood, **503**. *See also* Blood
Plasma, urinary system, 469–70
Plasma membranes, **58**
  active transport across, 86
  as animal respiratory surfaces, 507
  antibiotic-resistant bacteria and, 61
  cell-signaling roles of, 87
  endomembrane systems and, 64–67
  evolution of eukaryotic, from prokaryotic, 306
  in exchanges with external environments, 464
  exocytosis, endocytosis, and transport of large molecules across, 86
  in formation of first pre-cells, 298
  functions of, 58
  nanotechnology and evolution of, 87
  nervous system signal transmission across, 579–80
  passive transport as diffusion across, 83–84
  resting potentials and action potentials across, 577
  sensory transduction across, 587–88
  structure of, 60–61
  transport functions of, in cellular work, 83–87
  water balance and osmosis across, 84–85
Plasmids, **222**–24
Plasmodesmata, 611–12
Plasmodial slime molds, **309**
Plasmodium, 308
Plasmolysis, plant, 85
Platelets, **505**
Plate tectonics, macroevolution and, 283
Platyhelminthes phylum, 344
Pleasure center, hypothalamus, 583
Pleiotropy, **160**
Plistospilota guineensis, 637
Pneumonia, 61, 230, 303*f*
Pneumonic plague, 304
Poaching, DNA profiling and elephant, 226
Poison dart frogs, 430

Poisons, enzyme inhibition of, 82
Polar bears
  effects of global climate change on, 372–73, 399
  in polar ice biome, 390
Polar bodies, human, 557
Polar ice, **390**
Polar molecules, **28**
Poliovirus, 190–91, 525
Pollen grains, **323**, **618**
  angiosperm, 324, 617, 618–19
  gymnosperm, 323
  as plant sperm, 317
Pollination, **619**
  angiosperm, 618–19
  by animals, 637
  by insects, 352, 621
Pollution
  biological magnification of, 433
  bioremediation and phytoremediation of, 624–25
  chemical cycling and nutrient, 443
  declining biodiversity and, 428
  effects of, on human lungs, 510
  of freshwater biomes, 380–81, 392–93
  global water cycle and, 391
  of marine biomes, 383
  prokaryotes and bioremediation of, 305
  from synthetic pesticides, 416
  toxins in (*see* Toxins)
Polychaetes, 345*f*, **346**
Polygenic inheritance, **160**
  genetic variation and, 257
  human height as, 160–61
Polymerase chain reaction (PCR), **227**
Polymerization, 297
Polymers, **39**
  abiotic synthesis of, in origin of life, 297
  as linked monomers, 39
  nucleic acids as, 49–50
  proteins as, 47
Polynucleotides, **174**–75
Polynucleotides, DNA strands as, 50
Polypeptides, **47**. *See also* Proteins
  as amino acid chains in proteins, 47–48
  gene regulation of activation and breakdown of, 204
  synthesis of, in gene expression, 178–79, 184–85 (*see also* Gene expression)
Polyp form, **342**
Polyploidy, sympatric speciation and, 276–**77**
Polysaccharides, **42**, 100*f*
Ponds, 380
Pons, human, 583
Population density, **405**
  interspecific competition and, 429
  in population ecology, 405
  tropical forest fragmentation and, 446
Population ecology, **375**, 402–3, **404**–23
  applications of, 412–16
  biological control of pests and, 414–15
  biological invasions in, 402–3, 415, 421
  case study on biological control of kudzu, 415
  conservation of endangered species and, 412
  human population growth in, 417–21
  humans as invasive species in, 421
  integrated pest management and, 416
  invasive species and, 413–14
  life history traits as evolutionary adaptations in, 406–7
  life tables and survivorship curves in, 406
  overview of, 404–7
  population age structure in, 405
  population density in, 405
  population growth models in, 408–11
  populations in, 375
  sustainable resource management and, 412–13
Population growth
  cycles of, 411
  density-dependent factors limiting, 410
  density-independent factors limiting, 411
  exponential, 408
  interspecific competition and, 429
  logistic, 409
  logistic vs. exponential, 409
  models of, 408–9
  in population ecology, 404
Population momentum, **418**–19
Populations, **244**, **375**, **404**
  age structure of, 405
  analyzing gene pools of, 258–59
  density of, 405
  as level of life, 5*f*
  life tables and survivorship curves for, 406
  mechanisms of microevolution of, 260–62
  microevolution based on genetics of, 259
  population ecology and, 375, 404
  public health science and, 259
  sources of genetic variation in, 257–58
  as units of evolution, 244–45, 253, 256–57 (*see also* Evolution)
Pores, nuclear, 62, 63
Porifera phylum, 341
Porpoises, 360
Positive blood types, 159
Positive feedback, **466**, 568
Positive pressure breathing, 511
Post-anal tail, **354**
Posterior pituitary, 539*t*, **540**
Postzygotic barriers, **273**
Potassium (K), fertilizers with, 627
Potatoes
  genetically modified, 221
  genome of, 230
Potential energy, **76**
  in neurons, 577–78
Pottos, 361
Pouched mammals. *See* Marsupials
Prairie. *See* Temperate grasslands
Praying mantises, 637
Precambrian era, 280–82, 339
Pre-cells, formation of first, 298
Precipitation
  effects of, on distribution of terrestrial biomes, 384–86
  global climate change and, 373, 375
  in global water cycle, 391
Predation, **430**
  in community ecology, 430–31
  evolution of lizard horn length as response to, 254
  extinction of predators by humans and, 421
  by fungi, 328*f*
  by lionfish, 402–3
  in savannas, 387
Predictions, scientific method and, 15–16. *See also* Case studies
Pregnancy
  childbirth, 568
  contraception to prevent, 559–60
  female reproductive cycle and, 559
  genetic testing during human, 157
  gestational diabetes and, 544
  home test for, 522, 559
  iron deficiency and, 512
  of postmenopausal women, 570
  stages of human, 564–67
Premature birth, 567
Prenatal genetic testing, 565
Prepuce, **554**
  female, 555
  male, 554
Pressure
  human ear and, 592–93
  sensory receptors of, 588
Pressure-flow mechanism, **631**
Prevention, cancer, 214
Prey, 430. *See also* Predation
Prezygotic barriers, **272**–73
Primary cell walls, 611–12
Primary consumers, **432**–34
Primary electron acceptor, photosystem, **113**
Primary growth, plant, **613**–14
Primary immune response, **524**
Primary oocytes, **556**
Primary phloem, 614–15
Primary plant tissues, 613
Primary production, ecosystem energy flow and, **438**–39
Primary spermatocytes, **556**
Primary structure, protein, **47**–48*f*
Primary succession, **436**
Primary xylem, 614–15
Primates, **361**
  emergence of, in history of life, 295
  evolution of humans and, 361–62 (*see also* Human evolution; Humans)
  genetic relationships among, 251*f*
  as mammals, 361
Principles of Geology (book), 247
Prions, **194**
Probability, rules of, 152–53
Producers, **92**, **432**
  in chemical cycling, 440–43
  consumers vs., 92
  in ecosystem energy flow and chemical cycling, 6, 437
  photosynthetic autotrophs as, 108
  plants as, 9
  in trophic structure food chains, 432–33
Products, chemical reaction, **28**
Profiling, DNA. *See* DNA profiling
Progesterone
  after childbirth, 568
  birth control pills of synthetic, 560
  in human female reproductive cycle, 546, 558–59
Progestins, **546**
Programmed cell death, **564**
Progressive retinal atrophy (PRA), Labrador retrievers and, 151
Prokaryotes, **294**, 299–305. *See also* Archaea; Bacteria
  Bacteria and Archaea domains of, 9, 288, 302–3 (*see also* Archaea domain; Bacteria domain)

Prokaryotes (*Continued*)
bioremediation using, 305
cells of (*see* Prokaryotic cells)
chemical cycling by, 305
as decomposers, 433
distribution and significance of, in biosphere, 299
ecological impact of, 305
eukaryotic evolution from symbiotic, 306
evolution of glycolysis in, 103
forms of, 300–301
in history of life on Earth, 294
nutritional modes of, 302
reproduction of, 301
structure and function of, 300–302
Prokaryotic cells, **7**, **58**. *See also* Cells
eukaryotic cells vs., 7–9, 58 (*see also* Eukaryotic cells)
gene regulation in, 200–201
shapes of, 300–301
Prolactin, 568
Promoters, DNA, **201**
Promoters, transcription, **181**
Pronghorn antelope, evolution of, 421
Properties, of life and emergent, 4–5*f*
Prophages, **189**
Prophase, mitosis, 126*f*, **127**, 134*f*
Prophase I, meiosis I, 132*f*, 134*f*
Prophase II, meiosis II, 133*f*
Prostaglandins, 588
Prostate cancer, 129, 554
Prostate gland, **554**
Protease inhibitors, anti-HIV/AIDS, 193
Proteins, **46**–48
abiotic synthesis of, in origin of life, 297
amino acids as monomers of, 46 (*see also* Amino acids)
in antibiotic-resistant bacteria case study, 61
as antigen receptors, 522
ATP and cellular work of, 79
bacterial, 303
in cell cycle control system, 128
cellular respiration of, 100*f*
chemical digestion of, 477
denaturation of, 48
enzymes as, 37, 46*f*
essential amino acids for, 486
as evidence for evolution, 251
exocytosis, endocytosis, and transport of, across membranes, 86
fibers of, in connective tissue, 458–59
gene regulation of activation and breakdown of, 204
growth factors as, 211
histones as, 124
as hormones, 537
human dietary deficiencies of, 489
internal innate defense of defensive, 519–20
as macromolecules, 39
membrane (*see* Membrane proteins)
in molecular systematics, 287
in plasma membranes, 60
as polymers formed by dehydration reactions, 47
prions and misfolded, 194
proteomics and study of whole sets of, 233
self vs. nonself, 526–27, 529
shape and structure of, 48
synthesis of, by genes, 48–50 (*see also* Gene expression)
synthesis of, by ribosomes, 58, 62–63
synthesis of, with gene cloning, 222–23
synthesis of secretory, by rough ER, 64
types of, 46*f*
Proteomics, **233**
Protists, **306**–11*f*
cells of (*see* Eukaryotic cells)
cilia and flagella in movement of, 70
contractile vacuoles of, 67
cytoskeletons and movement of, 69
digestion by, 478
diversity and characteristics of, 307–8
Eukarya domain of, 9, 289
evolution of eukaryotic cells of, 306
evolution of multicellular life from unicellular colonial, 311
as pathogens, 432
as photosynthetic autotrophs, 108*f*
protozoans, 308
seaweeds, 310–11*f*
sexually transmitted diseases from, 560–61*t*
slime molds, 309
unicellular and colonial algae, 310
Protons, **25**
Proto-oncogenes, **211**
Protozoans, **308**
Proviruses, **193**
Prozac, 586
Pruning, apical dominance and, 608
Pseudocoelom, **340**–41*f*
Pseudopodia, **308**
P site, ribosome, 183–84
PSM protein, antibiotic-resistant bacteria and, 61
Psychological disorders, 580, 586
PTH (parathyroid hormone), **542**
Public health science, population genetics in, 259
Pueraria lobata, 415
Pulmonary arteries and veins, 498
Pulmonary circuit, **497**–98
Pulse, **501**
Pumps, circulatory system. *See* Hearts
Punctuated equilibria, speciation pace and, **277**
Punnett squares, **148**
law of independent assortment and, 150–51
law of segregation and, 148–49
Pupa, butterfly, 352*f*
Pupil, **589**
Pus, 520
Pyramid of production, ecosystem energy flow and, **438**–39
Pyruvic acid
in cellular respiration, 96–98
in fermentation, 101
Python molurus bivittatus, 468
Pythons
as invasive species, 414
thermoregulation by, to warm eggs, 468

Q

Quadriplegia, 581
Quaternary consumers, **433**
Quaternary structure, protein, 48*f*
Questions, scientific method and, 14–16. *See also* Case studies

R

Radial symmetry, **340**
Radiation
as carcinogen, 26
DNA damage from, 177
in leukemia treatment, 505
as mutagen, 187
phytoremediation of, 624–25
ultraviolet (*see* Ultraviolet (UV) light)
Radiation therapy, cancer, **129**
Radioactive isotopes, **26**. *See also* Radiation
phytoremediation of, 624–25
radiometric dating using, 282
as tracers in biological research and medicine, 26
Radiometric dating, **282**
Radon, cancer and, 26
Radula, **343**
Rage, steroids as cause of, 546
Rainbow bush locust, 351*f*
Rainfall. *See* Precipitation
Rain forests. *See* Temperate rain forests; Tropical rain forests
Rain shadow effect, 385
Random fertilization, genetic variation from, 136, 258
Random mutations, 257–58. *See also* Mutations
Ranges of species, global climate change and, 396
Rats
biological control of, 414
genome of, 230
Ratus norvegicus genome, 230
Ray-finned fishes, **356**
Rays, 356
Reabsorption, urinary system, **470**
Reactants, chemical reaction, **28**, 79*f*
Reaction center, photosystem, **113**
Receptor potentials, **587**
Receptor proteins
in cell signaling, 87
hormones and, 536–37
Receptors, nervous system, 579–80, 587–88. *See also* Nervous systems
Recessive alleles, **148**
dominant alleles vs., 148
human genetic disorders and, 154–56, 165–66
Recessive traits, 153–54
Recombinant chromosomes, 137
Recombinant DNA, **220**. *See also* Recombinant DNA technology
Recombinant DNA technology, 220–25
cutting and pasting DNA in, using restriction enzymes, 224
DNA (gene) synthesis in, 225
gene cloning in, 222–24
in genetic engineering applications, 220–22 (*see also* Genetic engineering)
techniques of, 222–25
using nucleic acid probes to select genes from genomic libraries in, 224–25
Recombination frequency, **164**
Rectum, **484**
Recycling, carbon footprints and, 398
Recycling, chemical. *See* Chemical cycling
Red algae, 310–11*f*
Red-and-black-striped stink bug, 351*f*
Red blood cells, **503**. *See also* Hemoglobin; Sickle-cell disease
blood doping and, 101, 221, 495
in blood tissue, 459
gene regulation of synthesis of, 204

high-altitude athletic training and production of, 504
oxygen transport by, 503–5
platelets and clotting of, 505
stem cells of, in leukemia treatment, 505
Red bone marrow, 595
Red-cockaded woodpeckers, population ecology and, 412
Red-crowned cranes, 359*f*
Red cones, eye, 590
Red-green colorblindness, **165**
Redox (oxidation-reduction) reactions, **95**
Red tide, dinoflagellates and, 310
Reduced hybrid fertility, 273
Reduced hybrid viability, 273
Reduction, **95**
Regeneration, **207**, 552
Regulation
enzyme inhibitors and, 82
feedback (*see* Feedback regulation)
homeostatic (*see* Homeostatic regulation)
of plant transpiration by stomata, 630
as property of life, 4
Relative abundance, species, **435**
Relative age, fossil, 282
Relative fitness, 262–**63**
Relay points. *See* Synapses
Releasing hormones, 540, 545, 558–59
Renal arteries and veins, 469
Repetitive DNA, **228**
in human genome, 231
in short tandem repeat (STR) analysis, 228
Replacement, cell, 122
Replication, DNA, 177
Repressor proteins, **201**
Reproduction, **552**
animal asexual, 552 (*see also* Asexual reproduction)
animal sexual, 553 (*see also* Sexual reproduction)
cellular (*see* Cellular reproduction)
effects of interspecific competition on, 429
evolution by natural selection and unequal success in, 11–12, 252–53, 262–63
fungal, 329
human (*see* Human reproduction)
life history traits and, 406–7
prokaryotic, 301
as property of life, 4–5*f*
reproductive barriers between species and, 272–73
species concepts and compatibility for, 271
terrestrial plant adaptations for, 316*f*–17, 322–23
vertebrate, 463*f*
Reproductive barriers, **272**
geographic barriers as, 274–75 (*see also* Geographic isolation)
prezygotic and postzygotic, 272–73
Reproductive cloning, **208**–9. *See also* Cloning
Reproductive cycle, human, **558**–59
Reproductive technologies, 568–70
infertility and, 568–69
legal issues on, 551
pregnancy for postmenopausal women using, 570
in vitro fertilization, 550–51, 569–70
Reptiles, **358**
birds as, 358–59 (*see also* Birds)
cladistics and phylogenetic trees of, 288
emergence of, in history of life, 295
nonbird, 358
physiological responses of, to environmental conditions, 378
Resolving power, microscope, **56**–57
Resources
ecological footprints and, 419–20
ecosystem services as, 424–25
sustainable management of, 412–13
Respiration, breathing as, 94. *See also* Breathing
Respiration, cellular respiration. *See* Cellular respiration
Respiratory surfaces, **507**–8
Respiratory systems, **507**–13. *See also* Circulatory systems
breathing and three phases of gas exchange in, 509
cardiovascular systems and, 497–98, 509, 512 (*see also* Cardiovascular systems)
cilia in, 70
effects of smoking on lungs in human, 198–99, 211–15, 512–13
in exchanges with external environments, 465
hemoglobin in gas transport in, 512
high-altitude evolutionary adaptations of human, 513
negative pressure breathing in, 511
respiratory surfaces in, 507–8
structure and function of, 510
vertebrate, 462*f*
Response
in cell signaling, 87
integration of stimulus and locomotor, 599 (*see also* Locomotor systems; Nervous systems; Senses)
of organisms to environments as property of life, 4–5*f* (*see also* Environments)
Resting potentials, **577**–80
Restoration ecology, **444**
biophilia and, 448–49
conservation biology and, 444 (*see also* Conservation biology)
landscape ecology and, 445
strategies of, 447
Restriction enzymes, **224**
Restriction fragment length polymorphism (RFLP) analysis, 229
Restriction fragments, **224**
Restriction sites, **224**
Results, scientific method and, 15–16. *See also* Case studies
Retina, **589**
Retinitis pigmentosa, founder effect and, 262
Retroviruses, **192**–93. *See also* HIV (human immunodeficiency virus)
Reverse transcriptase, **192**
gene synthesis using, 225
in retroviruses and HIV, 192–93
Reverse transcriptase inhibitors, 193
RFLP (restriction fragment length polymorphism) analysis, 229
R (radical) groups, 46
Rheumatoid arthritis, 522, 529*f*, **595**
Rhinoceros beetle, 351*f*
Rhizomes, **608**
Rhodopsin, 590, 599
Rhythm method, contraceptive, **559**–60
Ribbon model, DNA, 176*f*
Ribose, RNA and, 49–50, 175
Ribosomal RNA (rRNA), **183**
Ribosomes, **58**
functions of, 58, 62–63
rough ER and, 64
in translation phase of gene expression, 183
Ribozymes, RNA origins and, 298
Ribs, 594
Rice
genetically modified, 221–22
genome of, 230
Richness, species, 435
Right atrium, heart, 498–99
Right hemisphere, brain, 585
Right ventricle, heart, 498–99
Ring structures
in carbon skeletons, 38*f*
of glucose, 40
Ringworm fungus, 330
Ripening, fruit, 634
Risk
cancer, 214
cardiovascular disease, 506
Ritalin, 580
Rivers, 381, 383
RNA (ribonucleic acid), **49**
in gene expression, 63, 178–87 (*see also* Gene expression)
gene regulation of processing and breakdown of, 204
genetic code of, for amino acids, 179–80
as nucleic acid, 49–50
origin of, in origin of life, 298
processing of eukaryotic, 182
structure of, 50, 174–75
transcription of DNA to, 181
in viroids, 194
in viruses, 190–94
RNA polymerase, **181**
RNA splicing, **182**
Rocks, phosphorus cycle and, 441
Rodriguez, Alex, 535
Rods, retinal, **590**
Rod-shaped prokaryotic cells, 300
Roloff family, 156*f*
Root caps, **614**
Root-fungus symbiosis. *See* Mycorrhizae
Root hairs, **607**, 628
Root nodules, nitrogen-fixing bacteria and, 629
Roots, **316**, **607**
embryonic, 620
eudicot vs. monocot, 606
root nodule bacteria and, 629
root systems and, 607
as terrestrial adaptations, 316
uptake of water and essential nutrients from soil by, 628
Root systems, **607**
Rough ER, **64**
Roundworms (Nematoda), 230, **346**
RU-486 pills, 560
Rule of multiplication, **152**–53
Rules of probability, 152–53
Runners, stems as, 608

S

Saccharomyces cerevisiae genome, 230
Safe sex, 561
Safety issues, DNA technology, 235–36
St. John's wort, biological control of, 414
Salamanders
as amphibians, 357
macroevolution and paedomorphosis of, 279
reduced hybrid viability of, 273

Salem witch hunt, 331
Saliva, 479, 518
Salivary amylase, 482
Salivary glands, 64, **479**
Salmonella, 303
Salt marshes, 383
Salts. *See* Solutes
Sampling techniques, population ecology and, 405
Sand dollars, 353*f*
Sanitation, human disease and, 483
SA (sinoatrial) node, **500**
Sapwood, tree, 616
Sarcomeres, **596**–98
Satellite imagery, 386, 397
Saturated fatty acids, **43**–44
Savannas, **387**
Scabs, 505
Scallops, 343
Scanning electron microscope (SEM), 56*f*–**57**
Scarlet fever, 189
Scarlet king snakes, mimicry in, 430–31*f*
Scavengers, **433**
Schistosomes, 344
Schistosomiasis, 344
Schizophrenia, 580
Science, **14**
  biology as study of life using methods of, 4, 14 (*see also* Biology; Life)
  culture of, 17
  technology, society, and, 17–18
  theories in, 16–17
  types of, and scientific method in process of, 14–16 (*see also* Case studies)
Scientific method, science and, **14**–16. *See also* Case studies; Science
Scientific species names, 285
Sclera, **589**
Sclerenchyma cells, **612**
Scorpions, 348*f*
Scrapie, 194
Scrotum, **554**
Sea anemones, 342*f*, 552–53
Sea cucumbers, 353*f*
Seals
  in polar ice biome, 390
  population growth of, 409
Sea otters, as keystone species, 435
Sea sponges, regeneration of body parts by, 552
Sea stars
  as echinoderms, 353*f*
  as keystone species, 435
  life cycle of, 338
  regeneration of body parts by, 122–**23**, 552
Sea urchins
  as echinoderms, 353*f*
  gametic isolation of, 273
  sea otters, kelp, and, 435
Seaweeds, **310**–11*f*
Secondary cell walls, 611–12
Secondary consumers, **433**
Secondary growth, plant, **614**–16
Secondary immune response, **525**
Secondary oocytes, **557**
Secondary plant tissues, 614
Secondary spermatocytes, **556**
Secondary structure, protein, 48*f*
Secondary succession, **437**
Secondhand cigarette smoke, 513
Second trimester, pregnancy, 566–67
Secretion, urinary system, **470**
Secretory proteins
  exocytosis of, 86
  manufacture of, by rough ER, 64
Sedimentary rocks, fossil record and, 280
Seed coat, **619**
Seed leaves, 606
Seedless plants, 207, 318–21
Seed plants, 322–23. *See also* Angiosperms; Gymnosperms
Seeds, **319**, **619**
  abscisic acid in dormancy of, 635
  angiosperm, 325–26, 618–19
  dispersal of, 621, 637
  dormancy of, 619–20
  evolution of, 319
  germination of, 323, 618–20
  gibberellins in germination of, 635
  as gymnosperm terrestrial adaptations, 323
Seismic sense, elephant, 574–75, 588, 592
Selection, artificial. *See* Artificial selection
Selection, natural. *See* Natural selection
Selection, sexual. *See* Sexual selection
Selective serotonin reuptake inhibitors (SSRIs), 586
Self-fertilization, Gregor Mendel's experiments with, 146
Self-regulating mechanisms, 454–55
Self-replicating biological molecules, origin of, 298
Self vs. nonself proteins, 526–27, 529
Semen, 219, **554**
Seminal vesicles, **554**
Seminiferous tubules, **556**
Senses, 587–93
  case study on emergence of new, 598
  central nervous system and, 581–82, 587–88
  extrahuman senses and, 574–75, 588, 592, 598–99
  hearing, 592–93
  integration of, with locomotor response, 599
  sensory receptors and sensory transduction of, 587–88
  vision, 588–91
Sensitization stage, allergy, 528
Sensory adaptation, **587**
Sensory centers, brain, 582
Sensory input, nervous system, **576**, 584, 587–88, 599. *See also* Senses
Sensory neurons, **576**
Sensory receptors, 576
Sensory transduction, **587**–88. *See also* Senses
Sepals, flower, **324**, **617**
Septic shock, 303
Sequencing, genome, 8, 230–33. *See also* Genomes; Genomics
Serotonin, 580, 586
Sertraline, 586
Services, ecosystem, 424–25, 427
Severe combined immunodeficiency disease (SCID), 234, 529
Sewage treatment, prokaryotes and, 305
Sex, determination of human, 165
Sex chromosomes, **131**
  abnormality of number in humans, 140*t*
  DNA profiling of male ancestry using, 237
  homologous chromosomes and, 130*f*
  inheritance and, 165–66
  nondisjunction errors and abnormal numbers of, 139–40
  sex determination in humans and, 165
  sex-linked genes on, 165–66
  X chromosomes and Y chromosomes as, 131 (*see also* X chromosomes; Y chromosomes)
Sex hormones
  evolution of male aggression and androgen, 547
  production of, by gonads, 546
  as steroid hormones, 45, 546
  synthesis of, by smooth ER, 65
Sex-linked genes, **165**
Sexual dimorphism, **264**
Sexual intercourse, 562. *See also* Sexual reproduction
Sexually transmitted diseases (STDs), 308, **560**–61*t*
Sexual reproduction, **122**, 130–40, **553**, **617**. *See also* Reproduction
  angiosperm, 617–21
  animal, 338, 553
  asexual reproduction vs., 122, 130 (*see also* Asexual reproduction)
  evolutionary advantages of, 140
  evolution of bdelloid rotifers without, 137
  fungal, 329
  gametes in life cycles of sexual organisms, 131
  homologous chromosomes in, 130–31
  human (*see* Human reproduction)
  by Komodo dragons, 121
  meiosis errors in, 138–40
  meiosis in, 132–35
  origins of genetic variation in, 135–37, 258
Sexual selection, **264**
Shape
  animal body, in exchanges with external environments, 464
  cytoskeletons and cell, 69
  membrane proteins in cell, 83*f*
  molecular, 38
  prokaryotic cell, 300–301
  protein function and, 48
Sharks, 356
Sheep, reproductive cloning of, 208–9
Shells, egg, 358
Shingles virus, 191
Shivering, thermoregulation by, 471
Shoots, **316**, 633
Shoot systems, 607*f*–**8**
Short-night plants, 636–37*f*
Short tandem repeats (STRs), **228**
Shotgun approach, gene cloning, 224. *See also* Gene cloning
Shrikes, horned lizard evolution in response to predation by, 254
Shrimps, 349*f*
Siberian mammoth, DNA profiling of, 227
Sickle-cell disease, 47, **160**, 186, 265, 366
Side groups, amino acid, 46
Signal transduction pathways, **87**, **205**
  in cell signaling, 87, 205
  in gene regulation, 205
  hormones and, 536–37
  in sensory input, 587–88
Signal transmission, nervous system, 577–80. *See also* Nervous systems
  effects of drugs on brains and, 580
  from neurons to receiving cells, 579–80
  neurotransmitters in, 580
  resting potentials and action potentials in, 577
  signal propagation in, 578
  through neurons, 577–78

Silencers, DNA, **203**
Silent mutations, 186
Simple leaves, 609
Simpson, O. J. murder trial, DNA profiling and, 226
Single bonds, 27*f*
Single-celled organisms, 56, 464
Sister chromatids, **125**
Sixth mass extinction, 268–69. *See also* Mass extinctions
Size
  bottleneck effect of drastic reduction in population, 260–61
  of cells, 57*f*
  clutch, 410
  differences of, in sexual dimorphism, 264
  exercise and human brain, 31–32
  levels of life and, 4
  population, 404, 408 (*see also* Population growth)
Skeletal muscle, **460**, **596**–98
Skeletal systems, **594**–95
  diseases and injuries of, 595
  structure of, 594
  structure of bones of, 595
  vertebrate, 462*f*
Skeletons, carbon, 38–39
Skin
  cancer of human, 129, 214, 458
  cells of human, 74
  epithelial tissue of, 458
  as external innate defensive barrier, 518
  pigmentation of human, 366
  reptile scaled waterproof, 358
  as respiratory surface, 507–8*f*
  sensory receptors in, 588
Skulls
  human, 364, 594
  paedomorphosis of human, 279
  vertebrate, 354
Skunks, temporal isolation of, 272
Slash-and-burn agriculture, 327
Sleeping sickness, 307
Sliding-filament model of muscle contraction, 596–97
Slime molds, 309
Slow-twitch muscle fibers, 91
Sludge, 305
Slugs, 343
Small intestine, 461, **482**–83
Smallpox vaccination, 525
Smell receptors, 588
Smoking
  cancer and, 129, 214
  cardiovascular disease and, 506
  in development of lung cancer, 198–99
  effects of, on lungs, 510, 512–13
  effects of, on respiratory cilia, 70
  as mutagen, 187
Smooth ER, **65**
Smooth muscle, **460**
Snails
  mechanical isolation of, 273
  as molluscs, 343
Snakes
  habitat isolation of, 272
  mimicry in, 430–31*f*
  as reptiles, 358
  thermoregulation by, to warm eggs, 468
Snakestones, 245
Snowshoe hares, population cycles of, 411
Social issues
  antibiotic-resistant bacteria, 55
  asexual reproduction by Komodo dragons in captive breeding program, 121
  biofuels as green energy from photosynthesis, 106–7
  biology in everyday life, 3
  cellular respiration in aerobic vs. anaerobic lifestyles, 91
  discovery of hobbit people, 336–37
  DNA profiling in forensic science, 219
  dog breeding as longest-running genetic experiment, 144–45
  effects of global climate change on polar bears and penguins, 372–73
  effects of smoking tobacco on development of lung cancer, 198–99
  evolution in resistance to efforts to eradicate malaria, 242–43
  genetic testing and, 157
  harnessing cellular structures with nanotechnology, 75
  influenza viruses, 172–73
  lactose intolerance, 37
  legal issues on in vitro fertilization, 551
  life's dependence on water, 23
  lionfish as threats to coral reef communities, 402–3
  sixth mass extinction and, 268–69
  synthesis of artificial organisms by synthetic biology, 293
Sodium chloride
  in aqueous solutions, 31*f*
  in human diets, 488
  ionic bonding of, 27
  as table salt, 24
Sodium-potassium pump, 86
Soil
  as abiotic reservoir for nitrogen, 442
  as abiotic reservoir for phosphorus, 440, 441
  ecological succession of, after disturbances, 436–37
  fertilizers for, 627
  nutrients in, as abiotic factor in biosphere, 377
  plant acquisition of minerals from, 626
  plant nitrogen nutrition and bacteria in, 442, 628–29, 637
  uptake of water and essential nutrients from, by roots, 628
Solar energy. *See also* Light; Sunlight
  as abiotic factor in biosphere, 376
  conversions of, to chemical energy by light reactions, 110–14
  in ecosystem energy flow, 6, 437–39
  effects of, on distribution of terrestrial biomes, 384–86
  evolution of alternative photosynthetic pathways for, 115–16
  in freshwater biomes, 380
  photosynthesis and, 106
Solid state of matter, 24, 30–31
Solutes, **31**, **84**–85, 468–69
Solutions, **31**
Solvent, water as, **31**
Somatic cells, **130**
  genes in, 200
  homeotic genes and macroevolution of, 279
  homeotic genes in gene regulation of formation of, 205–6
  number of chromosomes in, 123*f*, 130
Sonoran desert food web, 434*f*
Sosa, Sammy, 534–35
Sound waves, hearing and, 593
Spacecraft, Mars exploration, 33
Space-filling models, 27*f*
Speciation, **270**–77
  artificial, by synthetic biology, 293
  biodiversity, Charles Darwin's theories, molecular biology, and, 270
  at ecosystem edges, 445
  evolution by natural selection and, 11–13
  mechanisms of allopatric and sympatric, 274–76
  patterns for pace of, 277
  reproductive barriers between species and, 272–73
  species concepts and, 271
Species, **271**
  biodiversity hot spots and endemic, 444
  concepts of, 271
  diversity of, in biodiversity, 426 (*see also* Biodiversity)
  diversity of, in communities, 435 (*see also* Communities)
  diversity of insect, 351
  ecological succession of, after disturbances, 436–37
  effects of global climate change on, 396, 399
  endangered (*see* Endangered species)
  evolution by natural selection of new (*see* Speciation)
  fixed species idea about, 245
  geographic distribution of, as evidence of evolution, 249
  grouping and naming of, 8–9, 285–89 (*see also* Systematics; Taxonomy)
  invasive (*see* Invasive species)
  loss of biodiversity through extinctions of, 425 (*see also* Extinctions)
  plate tectonics and geographic distribution of, 283
  population ecology and conservation of, 412 (*see also* Populations)
  sequencing of whole genomes of, 8, 230–33 (*see also* Genomes; Genomics)
  sixth mass extinction of, 268–69 (*see also* Mass extinctions)
  threatened (*see* Threatened species)
Species diversity, **435**
  in biodiversity, 426
  in communities, 435
  tropical forest fragmentation and, 446
Species richness, **435**
  species diversity vs., 435
  tropical forest fragmentation and, 446
Sperm, **553**
  angiosperm, 617–18
  fertilization by human, 562
  flagella of human, 70
  gametic isolation and, 273
  human infertility and, 568
  as male gametes in sexual reproduction, 122, 131, 553, 554
  nanotechnology and human, 75
  sex chromosomes in human, 165
  spermatogenesis of human, 556
Spermatogenesis, **556**
Sperm cells, plant
  in flower stamens, 146
  pollen grains and, 323

Spermicides, **560**
Sphagnum mosses, 319*f*
Spherical prokaryotic cells, 300
Sphinx moths, mimicry in, 431*f*
Spiders, 348
Spina bifida, 564
Spinal columns, 581, 594
Spinal cords, **581**
  in central nervous systems, 576, 581–82
  nervous tissue of, 461
Spinal taps, 582
Spines
  as herbivory defenses, 431
  leaves as, 609
Spiral prokaryotic cells, 300
Spirochetes, 300
Splints, bone, 595
Sponges (Porifera), **341**
Spontaneous generation, **296**
Spores, **320**, 618–19
Sporophytes, **320**, **618**
  angiosperm, 325, 618
  bryophyte, 320
  gymnosperm, 322–23
Sprinters vs. marathoners, 90–91
Squids, 343
Squirrels, allopatric speciation of, 275*f*
S-shaped curve, population growth rate, 409
SSRIs (selective serotonin reuptake inhibitors), 586
Stabilizing selection, **263**
Stamens, flower, 146, **324**, **617**
Standing water biomes, 380
Stapes, ear, 592–93
Staph infections, 61
Staphylococci, 300
Staphylococcus aureus, 303
  methicillin-resistant, 18, 61
Starches, 40–**42**
Start codons, 180, **184**
Starvation, human, 489, 491
States, water's, 29*f*, 30–31
States of matter, 24
Stem cells, **565**
  embryonic, 210, 565
  human gene therapy using, 234
  in leukemia treatment, 505
  lymphocytes and, 521
  therapeutic cloning using, 210
Stems, **608**
  embryonic, 620
  eudicot vs. monocot, 606
  photosynthetic, 609
  in shoot systems, 608
Stents, 506
Sterilization, contraceptive, 559
Sterilization, endospores and autoclave, 301
Steroid hormones, **45**
  abuse of anabolic, by athletes, 45, 534–35, 546
  adrenal gland production of, 545
  evolution of male aggression and, 547
  as lipid-soluble hormones, 45, 537
  rage caused by anabolic, 546
  sex hormones of gonads as, 546
  synthesis of, by smooth ER, 65
Sticky ends, DNA, 224
Stigma, flower, **324**, **617**, 619
Stimulus (stimuli), **577**
  nerve signals and, 577 (*see also* Signal transmission, nervous system)
  in nervous system integration of sensory input and locomotor response, 599
  plant responses to, 636–37
  sensory transduction and, 587–88
Stinging cells, 342
Stirrup, ear, 592–93
Stomach, **480**–81, 538
Stomach acid, innate defense of, 518
Stomata, **108**, **317**, **611**
  of C_3, C_4, and CAM plants, 115–16
  in photosynthesis, 108, 316*f*–17
  plant tissues and, 611
Stop codons, 180, **184**
Storage proteins, 46*f*
STR analysis, **228**
Strawberries, genetically modified, 221
Streams, 381
Streptococci, 300
Streptomycin, 55, 58
Stress
  adrenal gland hormones and, 544–45
  herpesviruses and, 191
Striated muscle, 460, 596
Strokes, 501, 505
Stroma, **68**, **108**
STRs (short tandem repeats), **228**
Structural formulas, 27*f*
Structural proteins, 46*f*
Structure, animal. *See* Animal structure and function
Strychnine, as herbivory defense, 431
Strychnos toxifera, 431
Sturtevant, Alfred H., 164
Substrates, enzyme, **82**
Succulent plants, CAM plants as, 116
Sucrase enzyme, 82
Sucrose
  as disaccharide, 41
  in phloem sap, 631
  sucrase enzyme and, 82
Sugar-phosphate backbone, DNA and RNA, **50**, **174**–75
Sugars. *See also* Glucose
  carbohydrates as, 40–42 (*see also* Carbohydrates)
  cellular respiration of, 100*f*
  creation of, from carbon dioxide in Calvin cycle, 115
  evolution of human craving for, 491
  nucleic acids and five-carbon, 49
  plant transport of, 630–31
  in sugar-phosphate backbones of DNA and RNA, 50, 174–75
Sugar sinks, plant, **631**
Sugar sources, plant, **631**
Sunflowers, phytoremediation by, 624–25
Sunlight. *See also* Light; Light reactions; Solar energy; Ultraviolet (UV) light
  as carcinogen, 129, 214
  in chemical cycling between photosynthesis and cellular respiration, 92–93
  DNA damage from, 177
  electromagnetic spectrum of radiation from, 110–11
  as mutagen, 187
  photosynthesis and, 106, 109
  plant photoperiod responses and, 636–37*f*
  plant phototropism and, 632–33, 636
Superbugs. *See* Antibiotic-resistant bacteria
Superior vena cava vein, 498, 502
Supernatural phenomena, science and, 14
Supporting cells, nervous system, **576**
Surface tension, water's, 29
Surgery. *See also* Medicine
  brain, 585
  for cancer, 129
  eye, 591
  heart transplants, 506
  for weight loss, 481
Surrogate motherhood, 569
Survivorship, population growth and, 406–7, 417
Survivorship curves, **406**
Sustainability, **392**
  coffee cultivation and, 605
  human impacts on biomes and, 392
  organic farming and, 627, 634
  sustainable development and, 448
  sustainable resource management and, 412–13, 419–20
Sustainable Biosphere Initiative, 448
Sustainable development, **448**
Swallowing, 479–80
Swamps, 381
Sweat, innate defense of, 518
Sweating, evaporative cooling by, 30, 454–55, 471
Swelling, inflammatory response, 520
Swim bladder, **356**
Swimmer's ear, 592
Swine flu, 172–73
Symbiosis, **306**, **315**
  endosymbiosis vs., 306
  lichens as, 332
  as mutualism, 430 (*see also* Mutualism)
  plant-fungus, 315, 332, 628
  in pollination and dispersal of angiosperms, 352, 619, 621
  of soil bacteria and plants, 442, 628–29
Symmetry, animal body, 340
Sympathetic division, autonomic nervous system, **582**
Sympatric speciation, **274**, 276
Synapses, **579**–80
Synaptic clepts, **579**–80
Synaptic terminals, **577**, 579–80
Syndromes, 139, 193
Synthetic biology, 293
Synthetic hormones
  anabolic steroids as, 45, 535
  plant, 634
Syphilis, 300
Systematics, **285**
  cladistics in, 287–88
  molecular biology as tool in molecular, 287
  phylogenetic trees and evolutionary relationships in, 286–87
  taxonomy in, 285–86
  three-domain system in, 288–89
Systemic circuit, **497**–98
Systemic lupus erythematosus (lupus), 529
Systole, **499**, 501

T

T4 bacteriophage, 188
Table salt, 24, 488. *See also* Sodium chloride
Tadpoles, 357
Taiga, **389**
Tail, RNA, **182**
Tail fibers, bacteriophage, 188
Tannins, as herbivory defenses, 431
Tapeworms, 344, 553
Taproots, 607

Target cells, hormone, **536**–38. *See also* Endocrine systems
Tarsiers, 361–62*f*
Taste receptors, 588
Tatum, Edward, 178
Taxol, 129
Taxonomy, **285**. *See also* Systematics
  binomial naming of species by Carolus Linnaeus and, 285
  Charles Darwin's ideas about, 244
  grouping of species in, 8–9
  hierarchical classification of species in, 285–86
  protist, 307–8
Tay-Sachs disease, 66
T cells, **521**
  cell-mediated immune response of, 526–27
  clonal selection and primary immune response of, 524–25
  as lymphocytes, 521
  recognition of invading antigens by, 522
Tears
  human eye secretion of, 589
  innate defense of, 518
Technology
  biotechnology, 220
  DNA (*see* DNA technology; Genetic engineering; Nanotechnology)
  reproductive (*see* Reproductive technologies)
  science, society, and, 17–18 (*see also* Science; Social issues)
Teeth, 24, 479
Telophase, mitosis, **127**, 134*f*
Telophase I, meiosis I, 133*f*, 134*f*
Telophase II, meiosis II, 133*f*
Temperate broadleaf forests, **389**
Temperate grasslands, **388**
Temperate rain forests, **389**
Temperate zones, **384**
Temperature, **30**
  as abiotic factor in biosphere, 377
  animal thermoregulation of body (*see* Thermoregulation)
  effects of, on distribution of terrestrial biomes, 384–86
  global climate change and, 372–73, 375
  greenhouse effect and, 394–95
  heat vs., 30
  human heat illnesses and, 454–55
  sensory receptors of, 588
Temporal isolation, 272
Temporal lobe, cerebral cortex, 584
Tendons, 459, **596**
Tendrils, 609
Terminal buds, **608**
Termination phase, transcription, 181
Termination phase, translation, 184
Terminators, transcription, **181**
Termites, protists and, 308
Terrestrial biomes, 384–90. *See also* Biomes
  abiotic factors in, 377
  animal osmoregulation in, 469
  animal respiration in, 508
  chaparral, 388
  climates, vegetation types, and biological communities of, 385–86
  coniferous forests, 389
  deserts, 387
  effects of climates on distribution of, 384–85
  effects of global climate change on, 397
  history of life and, 295
  human impacts on, 392
  polar ice, 390
  savannas, 387
  temperate broadleaf forests, 389
  temperate grasslands, 388
  tropical forests, 386
  tundra, 390
Tertiary consumers, **433**
Tertiary structure, protein, 48*f*
Testcrosses, **152**
Testes, **554**
  endocrine system functions of, 539*t*, 546
  human, 554
  human infertility and, 568
  spermatogenesis in human, 556
Testicles, **554**
Testicular cancer, 129
Testing, genetic. *See* Genetic testing
Testosterone
  anabolic steroids as synthetic, 45, 535, 546
  as androgen sex hormone, 546
  HCG and, 559
  Klinefelter syndrome treatment with, 140
Test-tube babies. *See* In vitro fertilization (IVF)
Test-tube cloning, 207*f*. *See also* Cloning
Tetany, 542
Tetrapods, **357**
  evolutionary tree of, 255*f*
  homeotic genes in macroevolution of, 279
  as vertebrates, 355*f*, 357
Texas barred tiger salamander, 357*f*
Thalamus, 583
Thalassemias, 265
Theories, scientific, 16–**17**. *See also* Science
Therapeutic cloning, **210**
Thermophiles, 303
Thermoreceptors, **588**
Thermoregulation, **467**
  animal mechanisms of, 467–68, 471*f*
  evolution of adaptations for, 471
  by human cardiovascular system, 506
  human heat illnesses and, 454–55
  reptilian, 358
Theropods, 359
THG anabolic steroid, athletic abuse of, 45
Thickening, secondary plant growth and, 614–16
Thick filaments, myofibril, **596**–98
Thigmotropism, **636**
Thin filaments, myofibril, **596**–98
Thinking, brain association areas and, 584–85
Thiomargarita namibiensis, 300*f*
Third trimester, pregnancy, 567
Thorax, insect, 350*f*
Thorns, as herbivory defenses, 431
Threatened species, **412**. *See also* Endangered species
  in biodiversity hot spots, 444
  population ecology and, 412
  species diversity and, 426
Three-domain system (taxonomy), **288**–89
Threshold, action potential, **577**
Thycydides, 525
Thylakoid membranes
  chloroplast pigments in, 112
  light reactions in, 114
Thylakoids, **108**
Thymine (T), 7, 49–50, 174–**75**, 193
Thymus, lymphocytes in, 521
Thyroid gland, **541**
  endocrine system functions of, 538–39*t*, 541–42
  iodine and, 24
Thyroxine, 541
Tibetans, high-altitude adaptations of, 513
Ticks
  as arachnids, 348*f*
  Lyme disease and, 304
Tigers, taxonomy of, 285*f*
Timekeeper, hypothalamus, 583
Tissues, animal, **457**–61
  of blood vessels, 500–501
  bone connective, 595
  connective, 458–59
  epithelial, 458
  magnetic resonance imaging (MRI) and water in human soft, 31–32
  muscle, 460
  nervous, 461
  in organs, 461
Tissues, as level of life, 5*f*. *See also* Tissues, animal; Tissues, plant
Tissues, plant, **610**
  cells and, 611–12
  primary growth of, 613
  secondary growth of, 614
  tissue systems of, 610–11
  vascular, 317
Tissue systems, plant, **610**–11
Toads, extinction of, 426*f*
Tobacco. *See* Smoking
Tobacco mosaic virus, 190
Tongue, **479**
Tools, *Homo habilis* and, 364
Tortoises, 270, 428
Touch, plant responses to, 636
Touch receptors, 588
Toxic shock syndrome, 303
Toxins. *See also* Pollution
  bacterial, 303–4
  biological magnification of, 433
  bioremediation of (*see* Bioremediation)
  dinoflagellate, 310
  as enzyme inhibitors, 82
  as herbivory defenses of plants, 431, 605
  as mutagens, 187
  phytoremediation of, 624–25
Toxoplasmosis, 308
Trace elements, **24**
Tracers, radioactive isotopes as, 26
Trachea, 480, **510**
Tracheal systems, insect, **508**
Tracheids, **612**
Traits, **146**
  family pedigrees of, 153–54
  heritable, 146, 253 (*see also* Inheritance)
  human, 366
  life history, 406–7
  wild-type, 153, 163
Tranquilizers, 580
Transcription, **178**
  in gene expression, 178–79, 185, 202*f*
  gene regulation and initiation of, 203
  phases of, 181
Transcription factors, DNA, **203**
Transduction. *See* Signal transduction pathways
Trans fats, 15–16, **44**
Transfer RNA (tRNA), **182**–83
Transformation, cancer cell, 129

Transgenic organisms, **221**–22. *See also* Genetically modified (GM) organisms
Transitional forms, fossil record of, 248
Translation, **178**, 182–85
  in gene expression, 178–79, 185, 202*f*
  gene regulation of initiation of, 204
  messenger RNA in, 182
  phases of, 184
  ribosomes in, 183
  transfer RNA in, 182–83
Translocation, **184**
Transmission electron microscope (TEM), 56*f*–**57**
Transpiration, **629**
  in global water cycle, 391
  plant water transport by, 629–30
Transpiration-cohesion-tension mechanism, **630**
Transplants
  heart, 506
  reproductive cloning and organ, 208–9*f*
Transportation, carbon footprints of, 398
Transport proteins, **83**
  in active transport, 86
  in facilitated diffusion, 84
  functions of, 46*f*
  as membrane proteins, 83
  transport work of, 79*f*
Transport vesicles, **64**
  exocytosis and, 86
  Golgi apparatus and, 65
  rough ER and, 64
Trash, carbon footprints and, 398
Trauma, brain, 585
Tree ring data, 615–**16**
Trees. *See also* Deforestation; Forests
  anatomical responses of, to wind, 379
  annual growth rings of, 615, 616
  cohesion and water transport in, 29
  gymnosperms, 322–23
  pathogens of, 432
  plant-fungus symbiosis of, 315
  relative abundance of, 435
  secondary growth of, 614–16
  water transport in, 629–30
Triathletes, 494–95. *See also* Athletes
Trichinosis, 346
Trichomonas, 308
Triglycerides, **43**–44
Triiodothyronine, 541
Trilobite beetle, 351*f*
Trimesters, pregnancy, **566**–67
Triplet code, amino acid, 179–80, 182–83
Trisomy 21, **139**
Tristan da Cunha, founder effect in, 262
Trophic structures, **432**–34. *See also* Food; Nutritional modes
  biological magnification in, 433
  energy flow in, 438–39
  food chains in, 432–33
  food webs in, 434
  human, 439
Trophoblast, **565**
Tropical dry forests, 386
Tropical forests, **386**
  effects of fragmentation on biodiversity of, 446
  human impacts on, 392
  precipitation and dry forests vs. rain forests, 386 (*see also* Tropical rain forests)
Tropical rain forests
  deforestation and loss of plant diversity in, 327
  effects of global climate change on, 397
  energy flow in, 438
  human impacts on, 392
  precipitation and, 386
  solar energy and, 384
Tropics, 327, **384**. *See also* Tropical forests
Tropisms, plant, 632–33, **636**
Trout, 381
Truffles, 314–15
Trypanosomes, 307
Tsunamis, 283*f*
Tubal ligation, **559**
Tube feet, echinoderm, 353
Tubers, **608**
Tube worms, 376*f*
Tubules, urinary system, **469**–70
Tumors, **129**. *See also* Cancer
  cancer and types of, 129
  case study on mutations causing childhood, 212
  development of colon cancer, 212–13
  evolution of cancer cells in, 215
  lung cancer, 198
Tumor-suppressor genes, **211**
Tundra, **390**, 397
Tunicates, **354**–55*f*
Turgid plant cells, 85
Turgor, plant, 85*f*, 611
Turner syndrome, 140
Turtles, 358
Twilight zone, marine biome, 382
Twins, 161*f*, 563
Two-kingdom system (taxonomy), 288
Tylenol murders, 99
Type 1 insulin-dependent diabetes, 544. *See also* Diabetes mellitus (diabetes)
Type 2 non-insulin-dependent diabetes, 544. *See also* Diabetes mellitus (diabetes)
Type I, II, and III survivorship curves, 406
Typhoid fever, 303

U

Ukraine nuclear reactor explosion, 26
Ulcers, 481
Ultrasound imaging, pregnancy and, 566–67*f*
Ultraviolet (UV) light. *See also* Sunlight
  as carcinogen, 129, 214
  DNA damage from, 187
  extrahuman vision and, 599
  human skin pigmentation adaptations to, 366
  as mutagen, 187
Umbilical cord, **565**, 568
Umbilical cord blood banking, 210
Undersea volcanoes, 33
Unicellular algae, 310
United Nations. *See* World Health Organization (WHO)
United States
  age structure of, 418–19
  childhood vaccinations in, 525
  Department of Agriculture, 236
  DNA profiling after World Trade Center attack in, 226
  ecological footprint of, 419–20
  economic costs of invasive species in, 413
  Endangered Species Act, 412
  FDA (*see* Food and Drug Administration (FDA))
  Federal Bureau of Investigation (FBI) CODIS database, 228
  Genetic Information Nondiscrimination Act of 2008, 237
  life table for population of, 406*f*
  National Aeronautics and Space Administration (NASA), 33
  National Cancer Institute, 523
  National Center for Biotechnology Information, 232
  National Institutes of Health (NIH), 236
  National Oceanic and Atmospheric Administration (NOAA), 403
Unity in diversity of life, 9, 180, 547
Unsaturated fatty acids, **43**–44
Uracil (U), 50, 174–**75**
Urea
  excretion of, by urinary systems, 469
  nitrogen in, 442
Ureters, urinary system, **469**
Urethra, **469**, **554**
  female, 555
  male, 554
  in urinary system, 469
Urey, Harold, 297
Urinary bladders, urinary system, **469**
Urinary systems
  in exchanges with external environments, 465
  homeostasis in human, 469–70
  vertebrate, 462*f*
Urine, **469**–70
Uterus, **555**, 558–59, 564–68. *See also* Pregnancy
UV light. *See* Ultraviolet (UV) light

V

Vaccination, **525**. *See also* Vaccines
Vaccines, **221**, **525**
  genetic engineering of, 221
  against HPV, 561
  immunization with, 525
  search for HIV/AIDS, 516–17
  for viruses, 191–92, 194
Vacuoles, **67**
  functions of, 67
  lysosomes and food, 66
  phagocytosis and food, 86, 478
Vagina, **555**
Valium, 580
Vampire devices, energy use by, 398
Variation, genetic. *See* Genetic variation
Variation, individual, 11, 252–53
Varicose veins, 502
Varmus, Harold, 211
Vascular bundles, plant stem, 610
Vascular cambium, **614**–15
Vascular systems, animal, 496–97
Vascular tissue, **317**, 319, 321. *See also* Phloem; Xylem
Vascular tissue system, **610**–11
Vas deferens, **554**, 559
Vasectomy, 554, **559**
Vectors, gene, **222**–24
Vegetable oils, 44
Vegetable plants. *See also* Plants
  artificial selection of, 12–13*f*
  unsaturated fatty acids in oils of, 44
Vegetarian diets, essential amino acids for, 486
Vehicles, flexible-fuel, 107
Veins, animal, **497**–98, 500–502

Veins, leaf, 606, 611
Venter, Craig, 232–33, 293
Ventilation. *See* Breathing
Ventricle, heart, **496**, 498–99
Venules, **497**, 501*f*, 502
Vertebrae, 354, 594
Vertebrates, 354, **355**–60
  adaptive defenses of, 518 (*see also* Adaptive defenses; Immune systems)
  characteristics of, 354
  as chordates, 354–55
  closed circulatory systems of, 496–97 (*see also* Cardiovascular systems)
  emergence of, in history of life, 295
  hormones and endocrine systems of, 463*f*, 536–37 (*see also* Endocrine systems)
  macroevolution of, from invertebrates, 279
  nervous systems of (*see* Nervous systems)
  organ systems of, 462*f*–63*f*
  phylogenetic tree of, 355*f*
  tetrapods as, 357
Vesicles, artificial, 87
Vesicles, transport. *See* Transport vesicles
Vessel elements, plant, **612**
Vestigial structures, evolution and, **250**
Viagra, 569
Vibrio cholera, 483
Villi, small intestine, 483
Vinblastine, 129
Virginia's warblers, 429
Viroids, 194
Viruses, **188**–94
  animal, 190–91
  antibiotics and, 18, 71
  bacteriophages, 188–89
  cancers caused by, 211
  conjunctivitis caused by, 589
  emerging, 194
  gene synthesis using reverse transcriptase from, 225
  HIV and AIDS, 192–93
  human gene therapy using, 234
  influenza, 172–73
  interferons as innate defense against, 519
  meningitis from, 582
  as pathogens, 432
  plant, 190
  sexually transmitted diseases from, 560–61
  structure of, 173
  vaccines against, to protect elderly humans, 192
  viroids and prions vs., 194
Visible light, 111. *See also* Light; Sunlight
Vision, 588–91
  cerebral cortex and, 584
  extrahuman, of ultraviolet light, 599
  eye function in, 589
  eye structure in, 589
  photoreceptors in, 590
  problems and corrections for, 591
Vitamins, **487**
  bacterial production of, in human large intestine, 484
  cancer prevention or survival and, 214
  essential, for humans, 487*t*
  Vitamin A deficiencies and, 222, 590
Vitreous humor, **589**
Vocal cords, **510**
Vocalizations, androgens and male, 547
Voice box, 480, 510
Volcanic carbon dioxide, 33
Voltage, resting potential and action potential, 577–78
Volume, hearing and, 593
Voluntary nervous system, 582
Volvox, 310–11
Vulva, **555**

W

Wallace, Alfred, 247
Warblers, 429
Warning coloration, **430**
Water, 29–33
  as abiotic factor in biosphere, 377
  as abiotic reservoir for biogeochemical cycles, 440
  acids, bases, and pH of solutions of, 32–33
  biological significance of floating of ice as solid, 30–31
  biomes and (*see* Freshwater biomes; Marine biomes)
  cellular balance of (*see* Water balance)
  in chemical cycling between photosynthesis and cellular respiration, 92–93
  cohesion of, 29
  conservation of, 23
  declining biodiversity and pollution of, 428
  as factor in search for extraterrestrial life, 33
  for global human population, 419
  global water cycle, 391
  human heat illnesses and drinking, 454–55
  human impacts on availability of, 392–93
  hydrogen bonding and polarity of, 28, 29
  hydrophilic molecules vs. hydrophobic molecules and, 42–43 (*see also* Hydrophilic molecules; Hydrophobic molecules)
  life's dependence on, 22–23, 29–33
  magnetic resonance imaging (MRI) and, 31–32
  in photosynthesis, 109
  physical states of, 29*f*
  plant acquisition of, 626
  plant sugar transport and, 631
  plant transport of, 612, 629–30
  in redox reactions, 95
  as solvent of life, 31
  temperature moderation by, 30
  water-splitting photosystems, 113–14
Water balance
  animal osmoregulation of, 468–69
  contractile vacuoles and protist, 67
  osmosis and, 84–85
Water-conducting cells, plant, 612, 629–30
Water intoxication (hyponatremia), animal, 85
Water-soluble hormones, 536–37
Water-soluble vitamins, 487*t*
Water vascular system, **353**
Watson, James, 175*f*
  discovery of structure of DNA by, 17, 175–77
  genome of, 233
Wavelengths, electromagnetic energy, **110**–11
Wax, ear, 518
Weapons, bacterial, 304. *See also* Bioterrorism
Weather, population growth and, 411. *See also* Climates
Weathering, chemical cycling and, 440, 441
Weight control, human, 474–75, 481, 485, 490–91. *See also* Obesity
West Nile disease, 352
Wetlands, **381**, 424–25
Whales
  evolution of, 248
  as mammals, 360
Wheat
  sympatric speciation of, 276
  wheat stem rust and wild, 426
Wheat stem rust, 426
White blood cells, **505**
  in blood tissue, 459
  defensive functions of, 505
  internal innate defense of, 519
  lymphocytes as, 521 (*see also* B cells; Lymphocytes; T cells)
  stem cells of, in leukemia treatment, 505
White truffles, 314–15
Whole-genome shotgun method, **232**–33
Wildfires, global climate change and, 397
Wildlife conservation, 412–13. *See also* Captive breeding programs
Wild mustard plant, vegetable plants as descendents of, 12–13*f*
Wild-type traits, **153**, 163
Wilkins, Maurice, 175, 177
Wilmut, Ian, 208
Wilson, Edward O., 448–49
Wind
  as abiotic factor, 377, 379
  seed dispersal by, 326*f*
Windpipe, 480, 510
Winged mammals, 360
Wings, bird, 359
Withdrawal method, contraceptive, 560
Wolves
  domesticated dogs as descendents of, 12–13*f*
  reproductive cloning of, 208–9*f*
Womb, 555
Women. *See* Females, human
Wood, **614**–16. *See also* Trees
Woodpeckers, population ecology and, 412
Work, cellular. *See* Cellular work
World Health Organization (WHO), 243, 475, 525
World Trade Center attack, DNA profiling after, 226

X

Xanax, 580
X chromosome inactivation, **202**–3
X chromosomes
  inactivation of, 202–3*f*
  nondisjunction errors and abnormal numbers of, 139–40
  as sex chromosomes, 130*f*–31 (*see also* Sex chromosomes)
  and sex determination of human females, 165

X-ray crystallography, 175
X-rays
  DNA damage from, 177
  as mutagens, 187
Xylem, **317**, **610**
  primary, 614–15
  secondary, 614–16
  in sugar transport, 631
  uptake of water and essential nutrients from soil by, 628
  as vascular tissue, 317, 610–11
  in water transport, 629–30
  wood as, 614
Xylem sap, **629**–30

Y

Y chromosomes
  DNA profiling of male ancestry using, 237
  nondisjunction errors and abnormal numbers of, 139–40
  as sex chromosomes, 130*f*–31 (*see also* Sex chromosomes)
  and sex determination of human males, 165
Yeasts
  budding of, 328*f*
  fermentation and, 102–3
  genome of baker's, 230
  infections by, 330
Yellow bone marrow, 595
Yolk sac, 565
Yucutan Peninsula meteor crater, 284*f*–85

Z

Zoloft, 586
Zooplankton, **382**
  biological magnification and, 433
  in marine biomes, 382
  in trophic structure food chains, 432–33
Zygotes, **131**, **553**
  angiosperm, 619
  embryos vs., 555
  human, 563–64
  reproductive barriers and, 272–73
  in sexual reproduction, 131, 553